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United States Patent [19]

Abileah et al.

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[54] NORMALLY WHITE TWISTED NEMATIC LCD WITH RETARDATION FILMS ON OPPOSITE SIDES OF LIQUID CRYSTAL MATERIAL FOR IMPROVED VIEWING ZONE

[75] Inventors: Adiel Abileah, Farmington Hills; Gang Xu, Royal Oaks, both of Mich.

[73] Assignee: OIS Optical Imaging Systems, Inc., Troy, Mich.

[21] Appl. No.: 167,652

[22] Filed: Dec. 15, 1993

[51] Int. Cl. 6 G02F 1/13

[52] U.S. Cl. 359/73

[58] Field of Search 359/73

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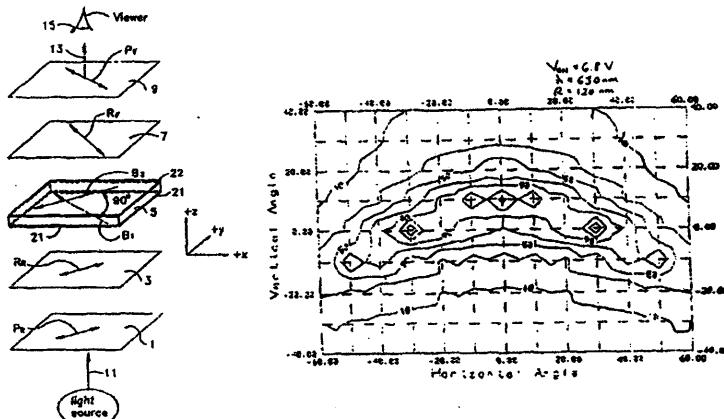
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Primary Examiner—Anita Pellman Gross
 Attorney, Agent, or Firm—Myers Liniak & Berenato

[57] ABSTRACT

A normally white twisted birefringent liquid crystal display having first and second retardation films having retardation values of about 80-200 nm on opposite sides of a liquid crystal layer for the purpose of expanding the viewing angles of the display. Also, the viewing zone of this normally white display can be shifted vertically by rotating the optical axes of the retardation films so as to position the viewing zone away from an inversion area.

48 Claims, 46 Drawing Sheets

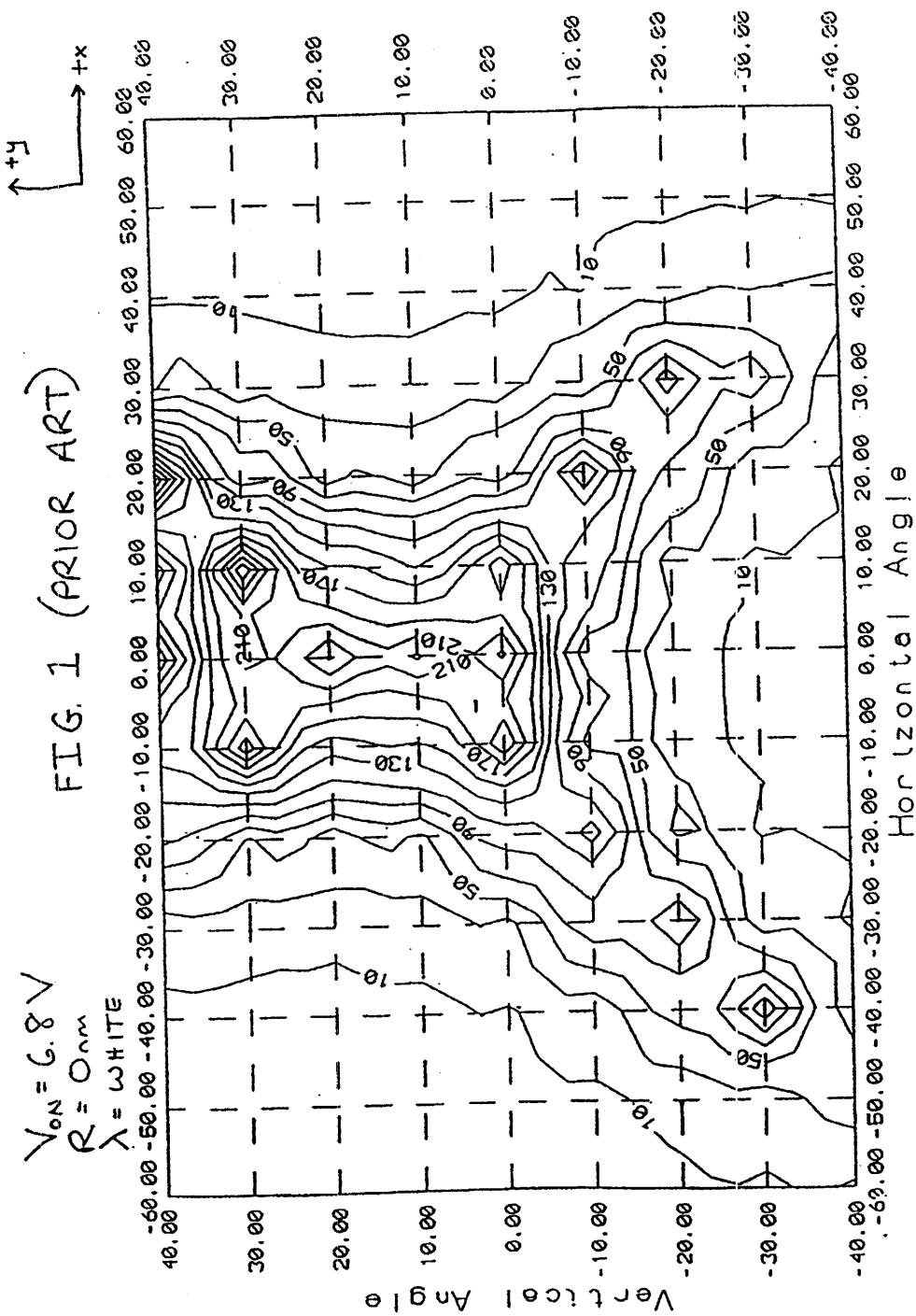


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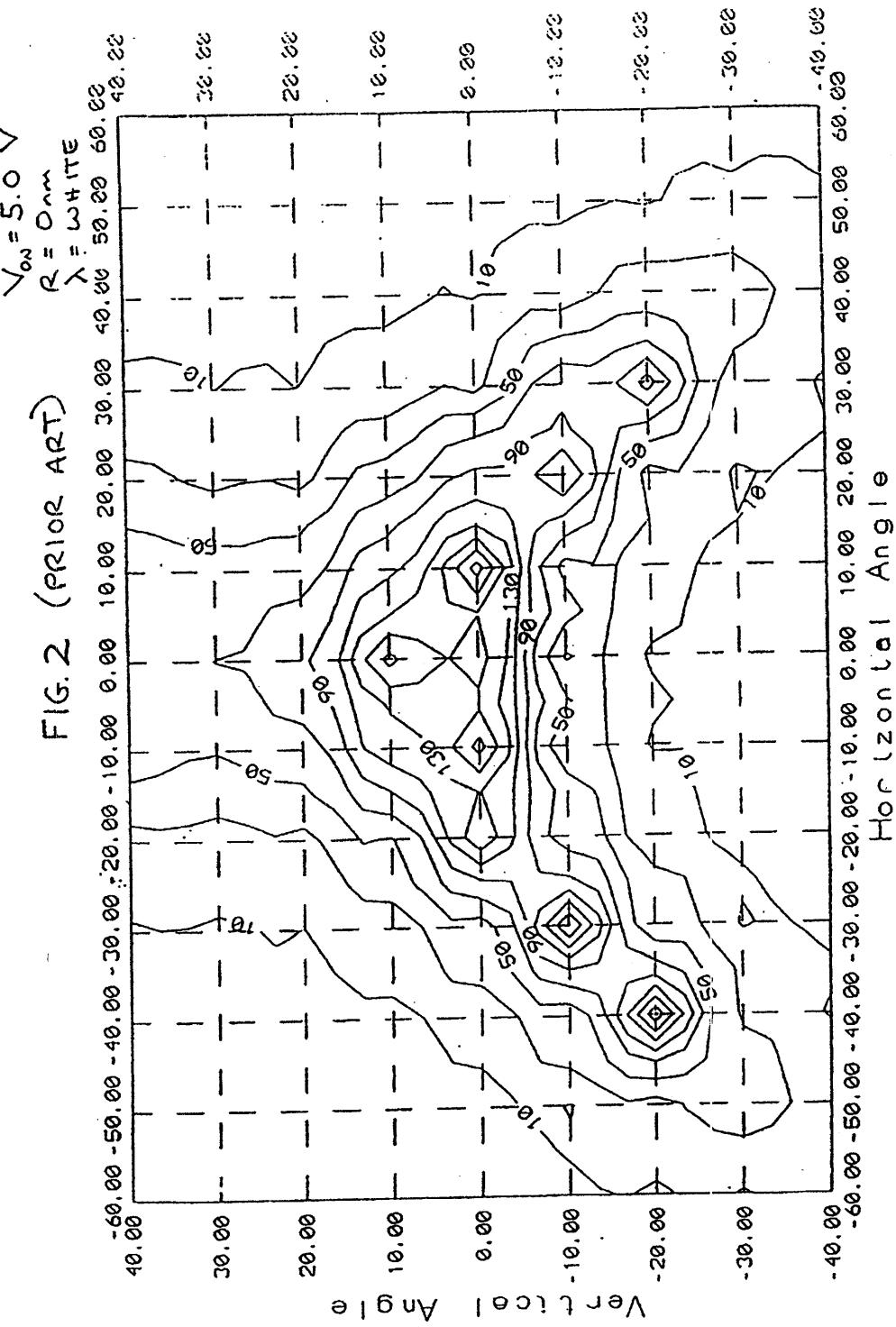


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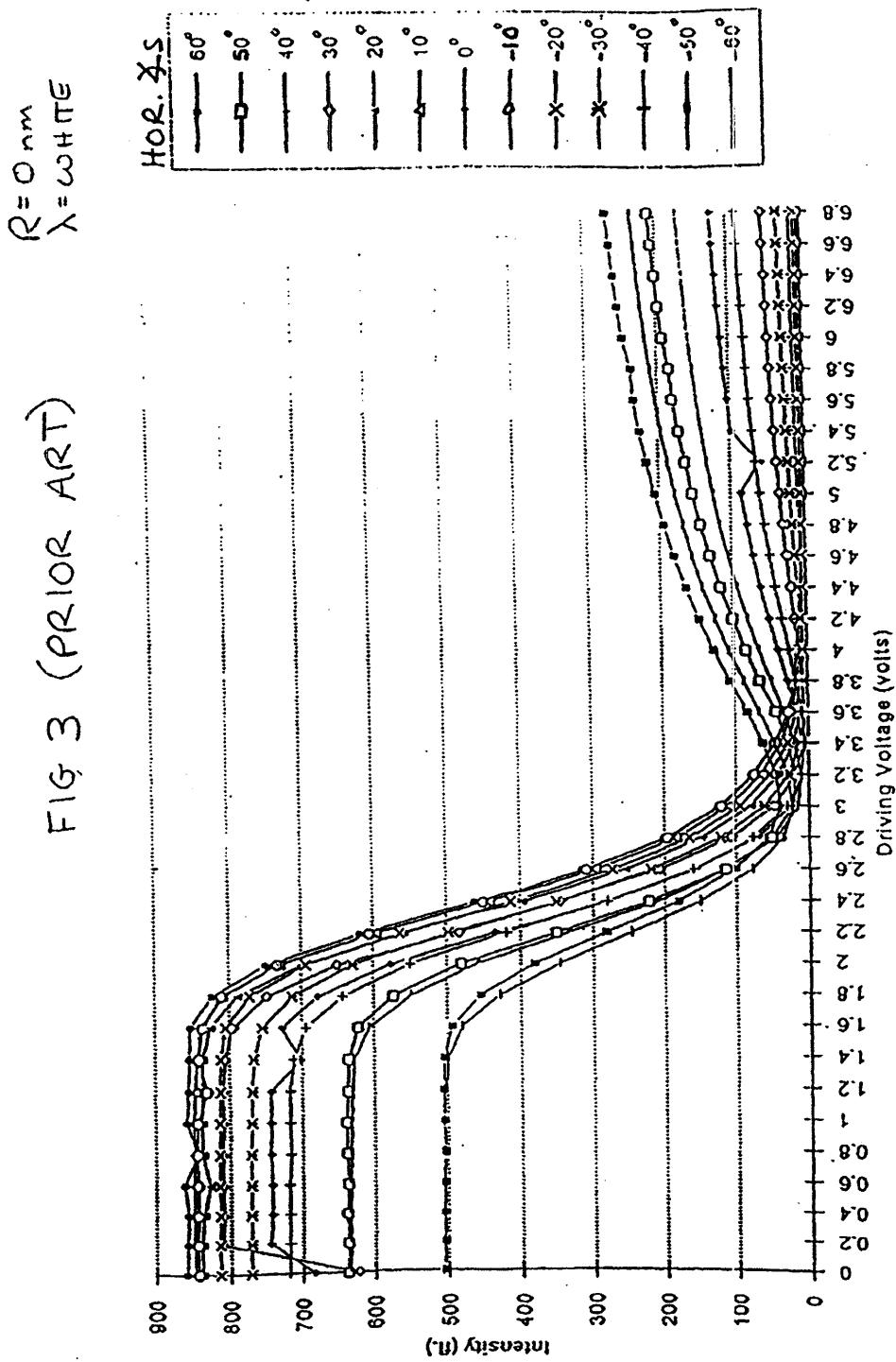


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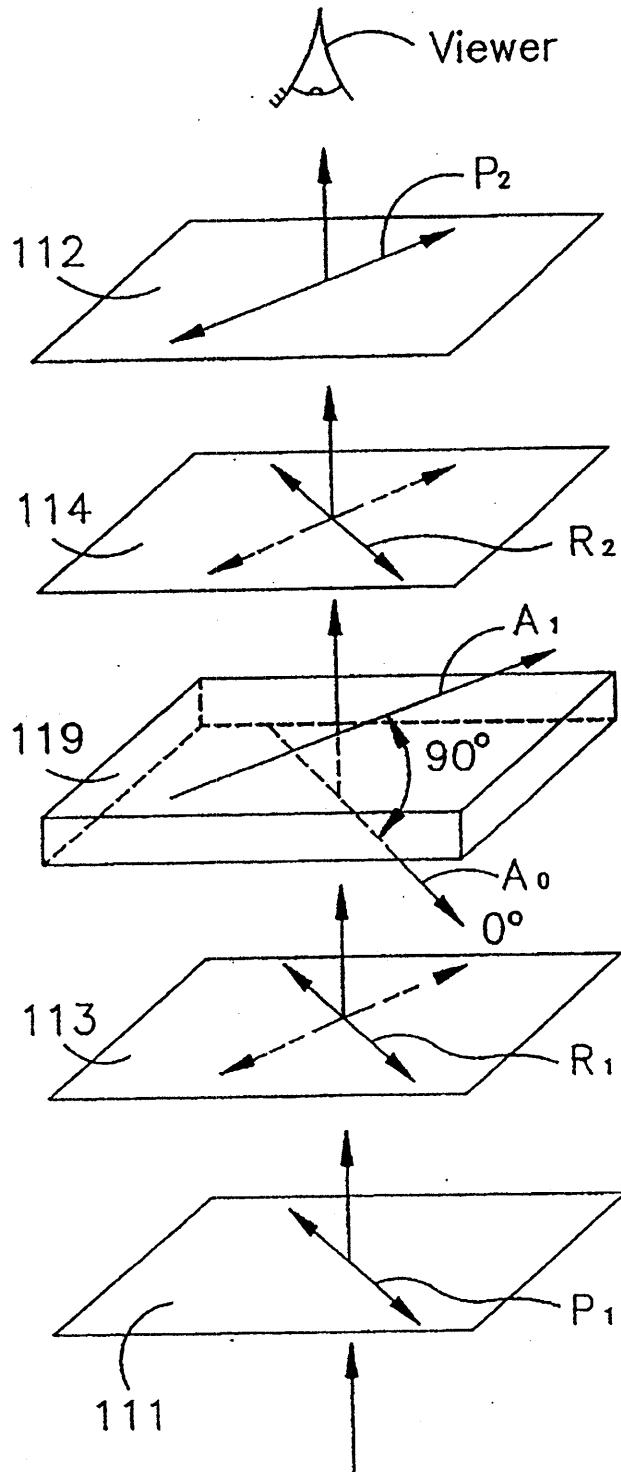
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Fig. 4 (Prior Art)



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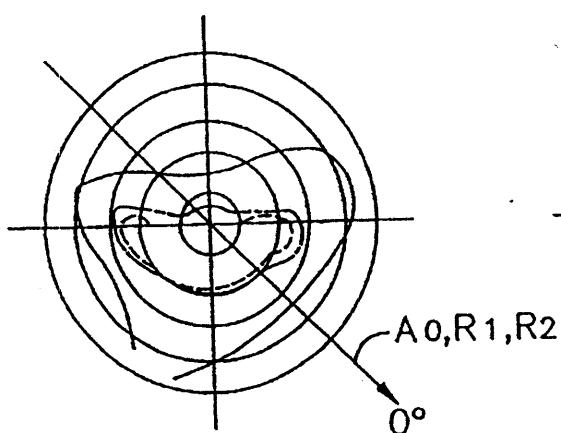


Fig. 5A (Prior Art)

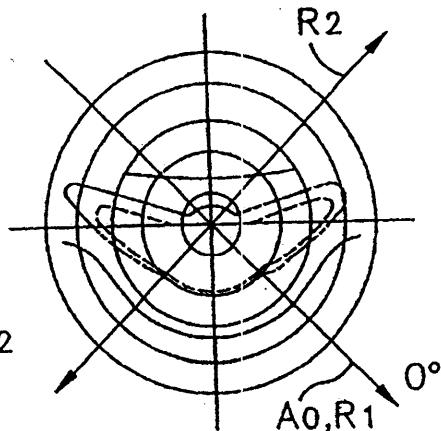


Fig. 5B (Prior Art)

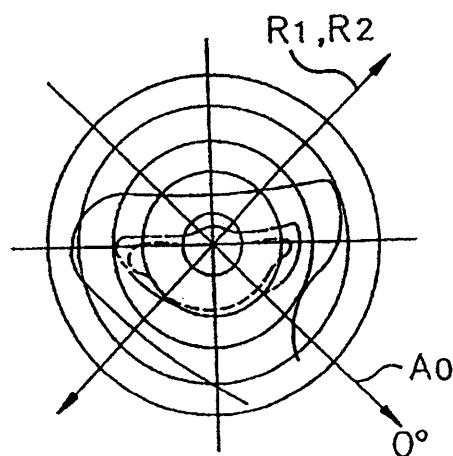


Fig. 5C (Prior Art)

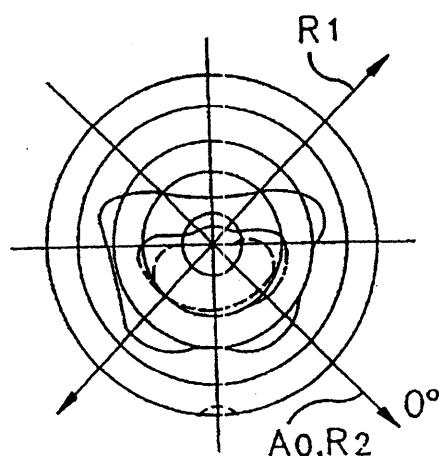


Fig. 5D (Prior Art)

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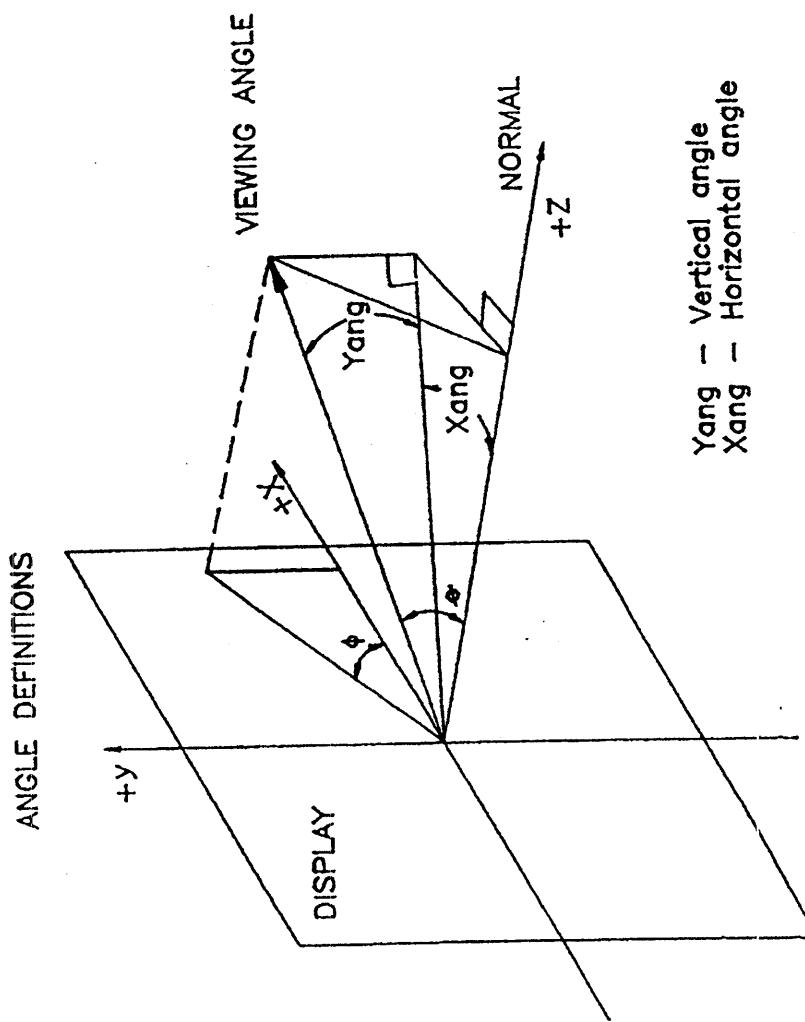


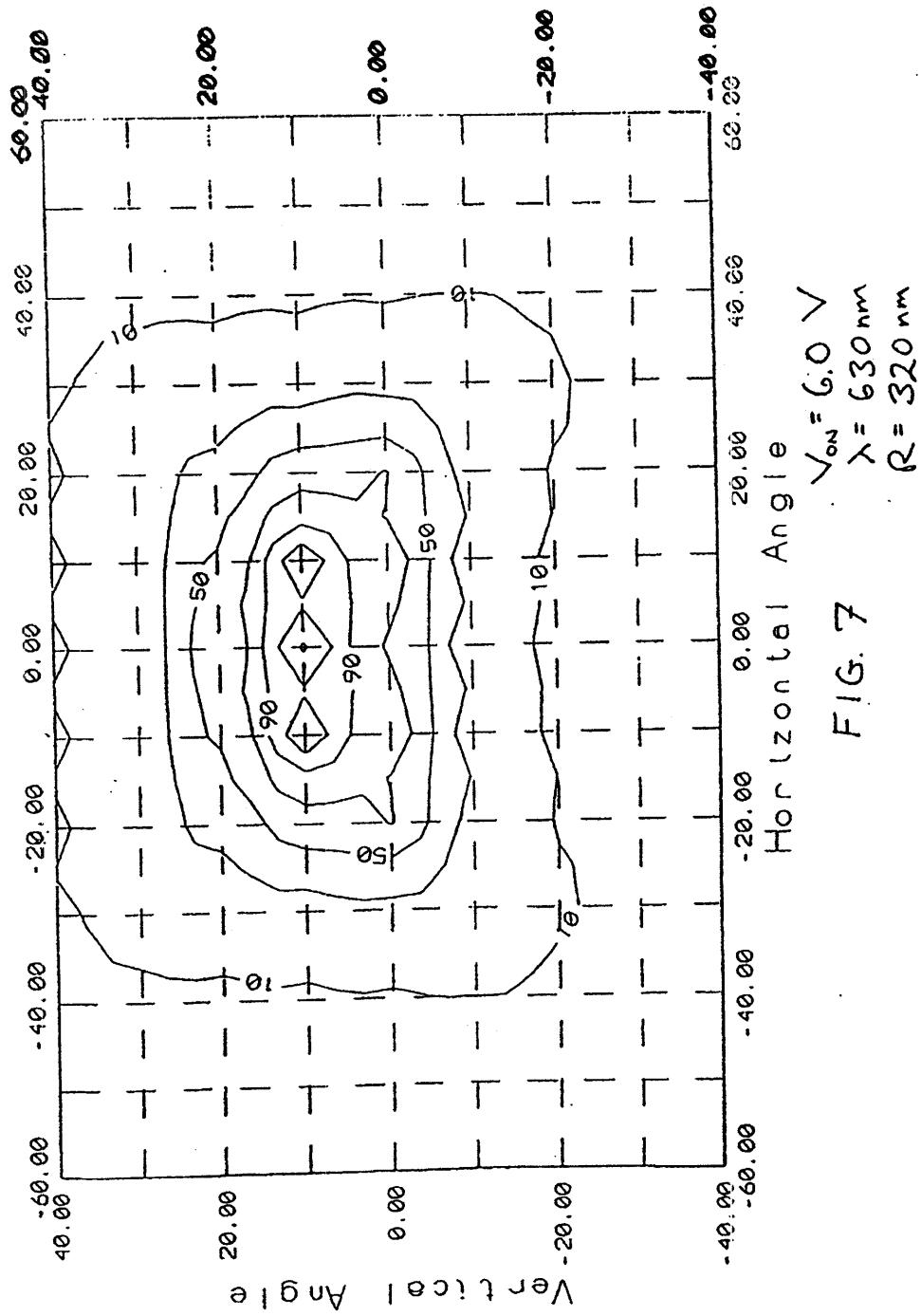
Fig. 6

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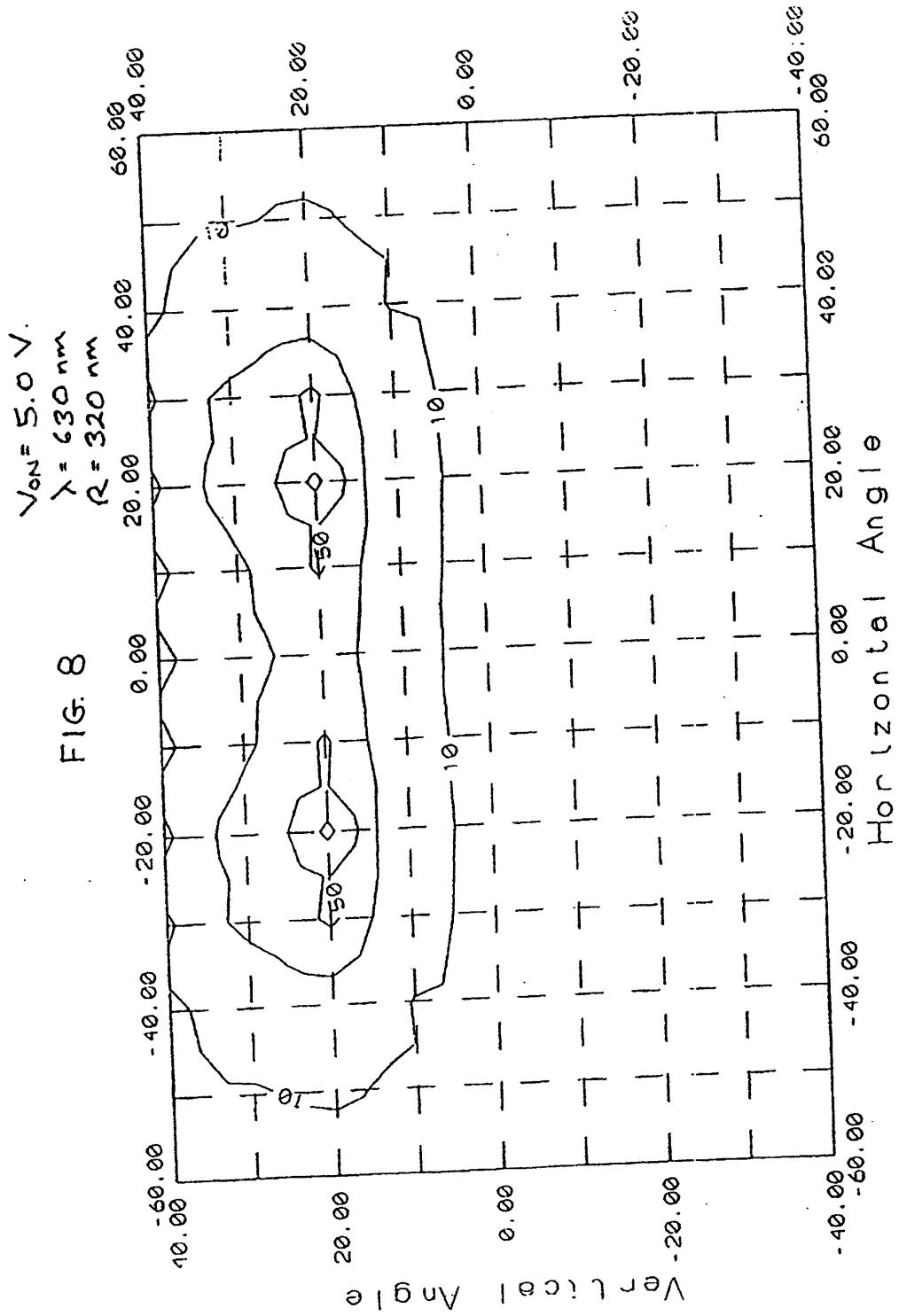


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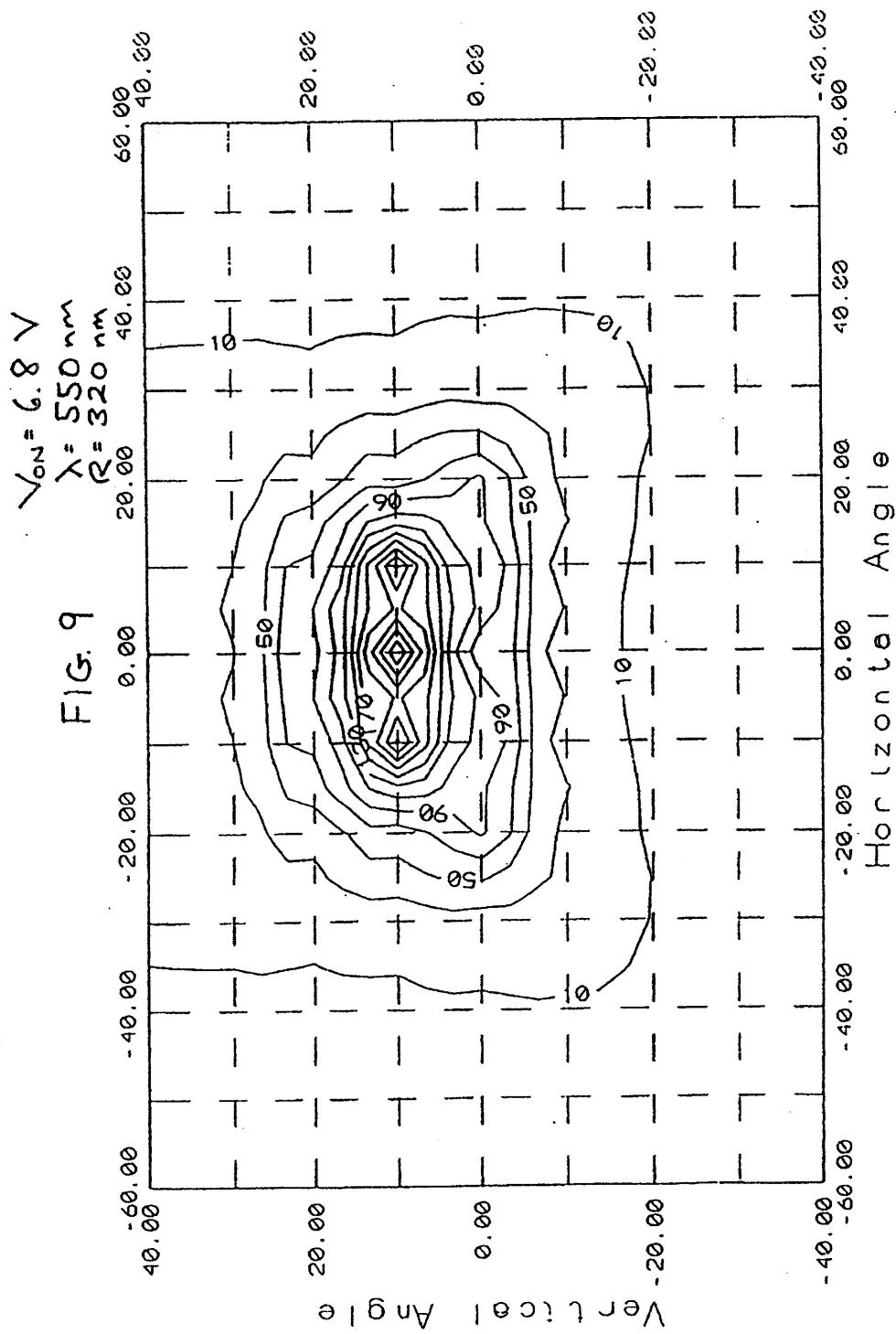


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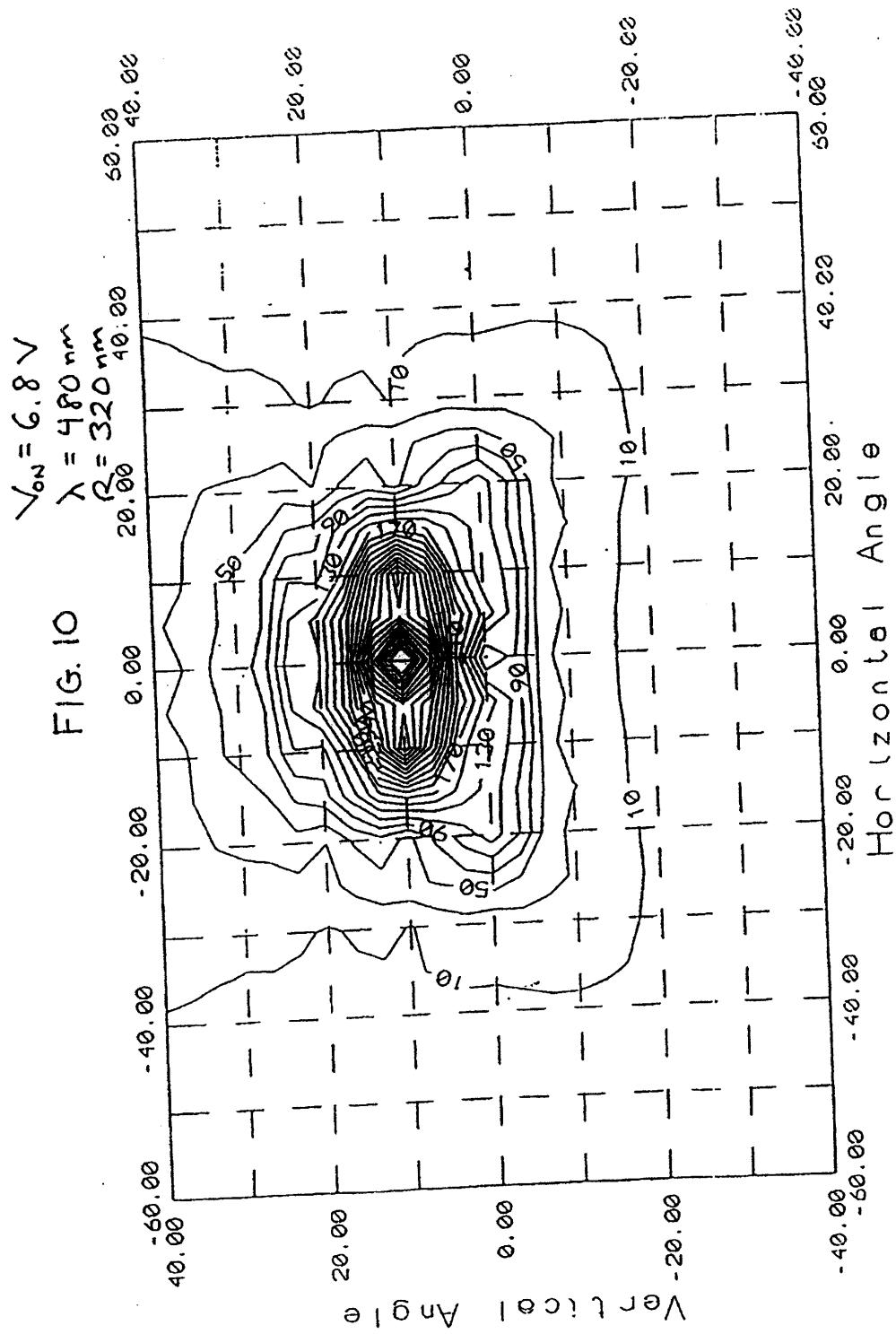


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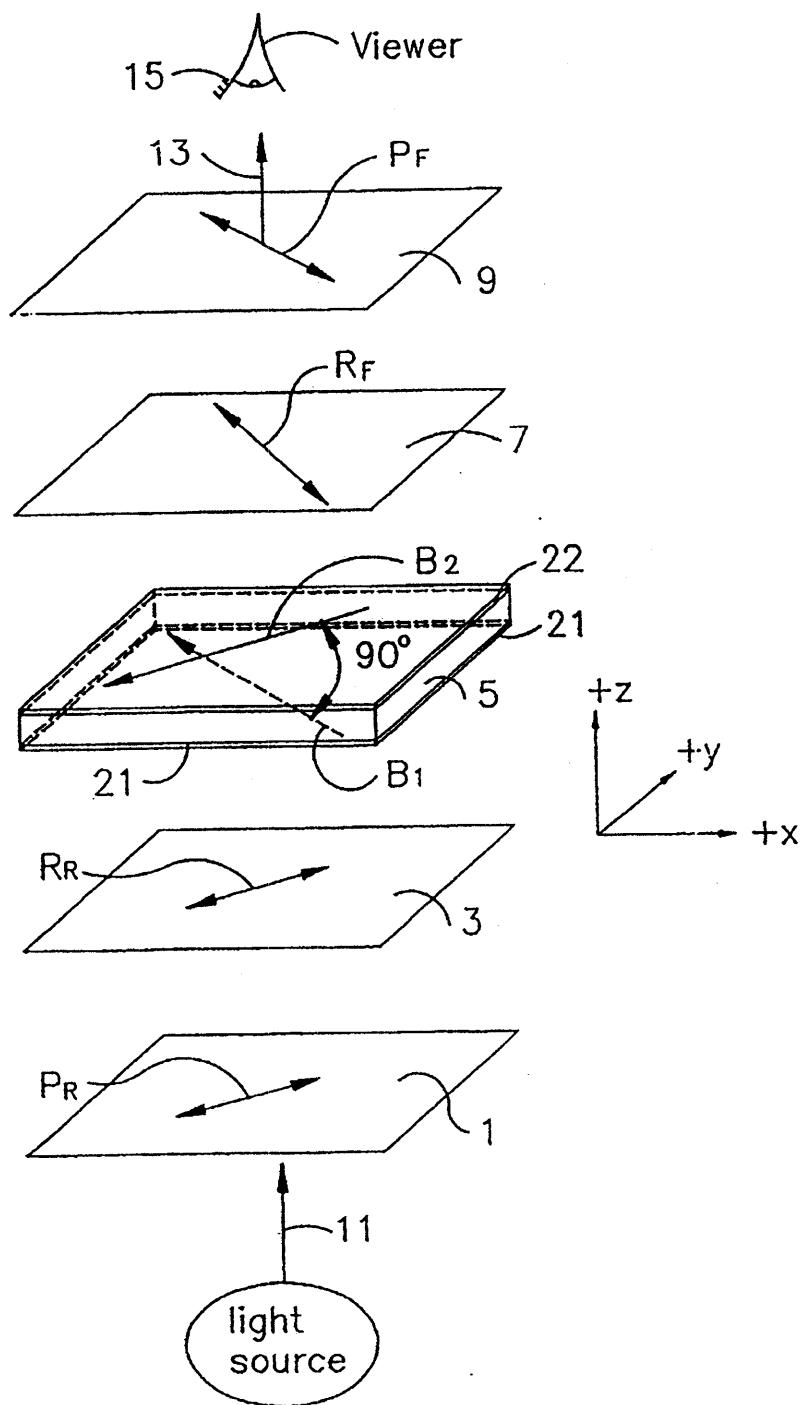
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Fig. 11(a)



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Fig. 11(b)

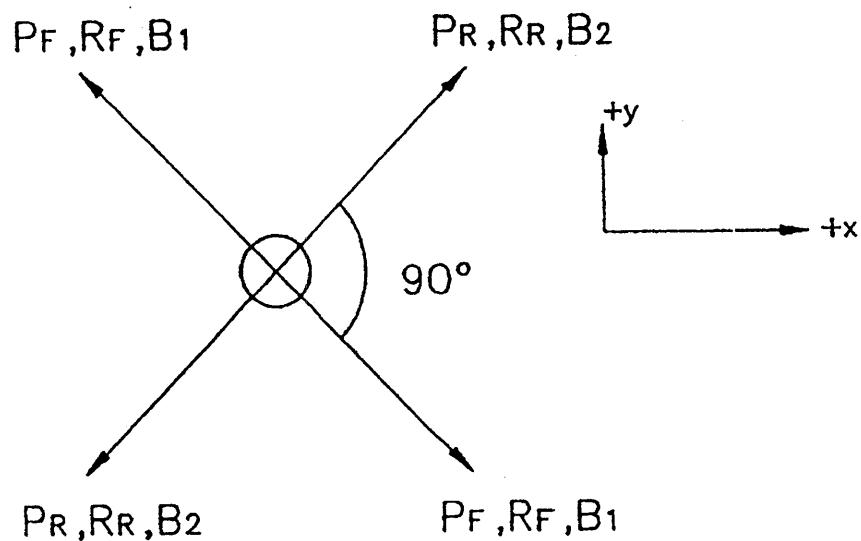
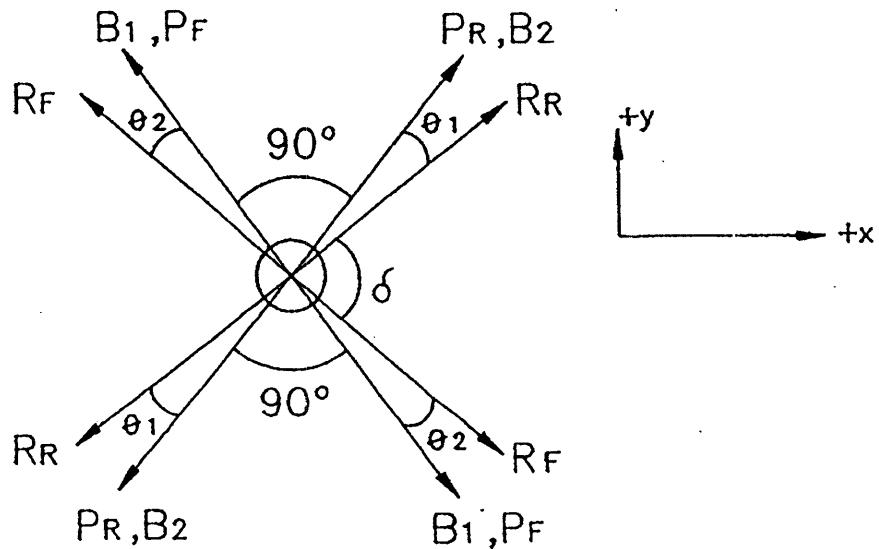


Fig. 11(c)

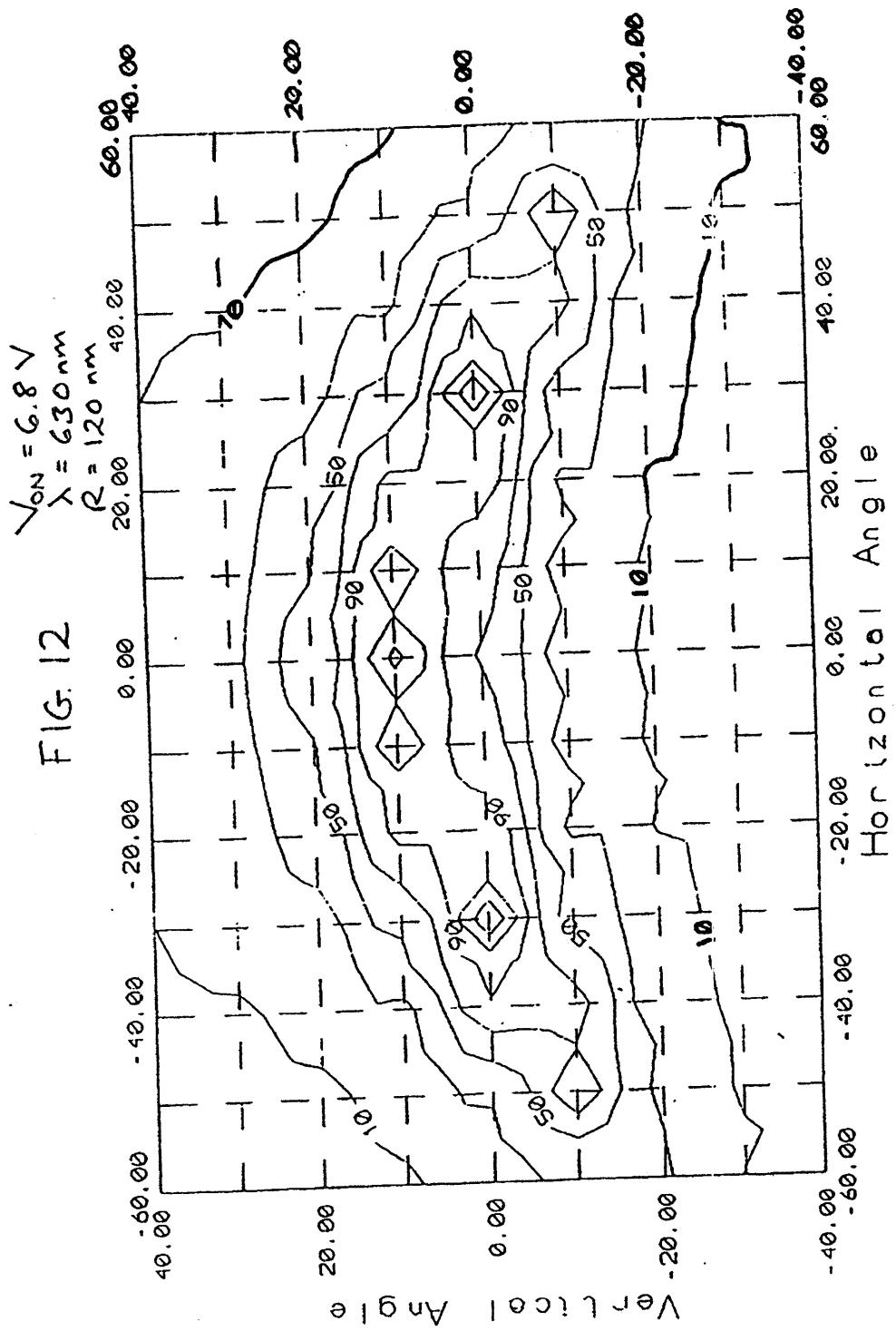


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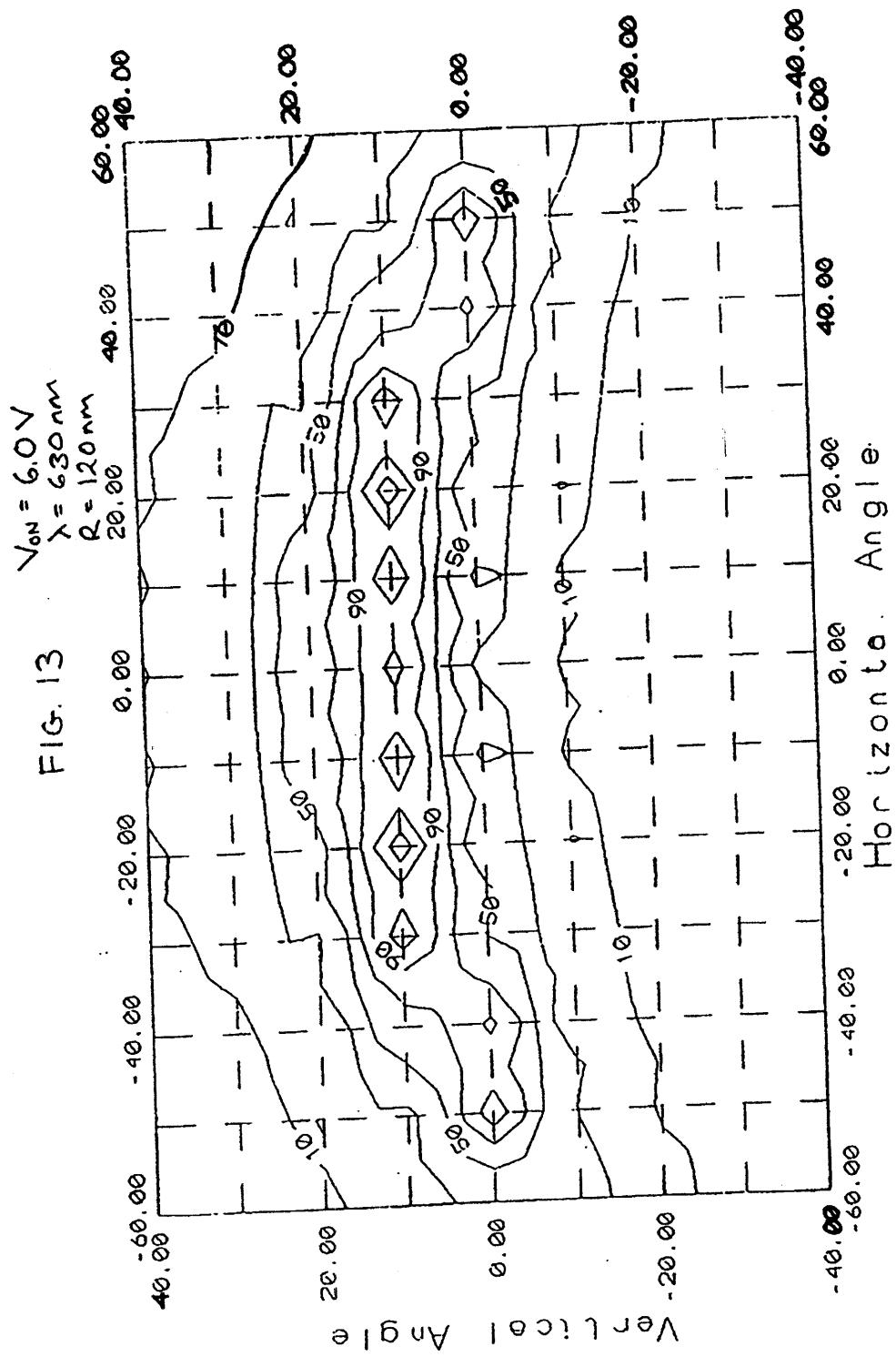


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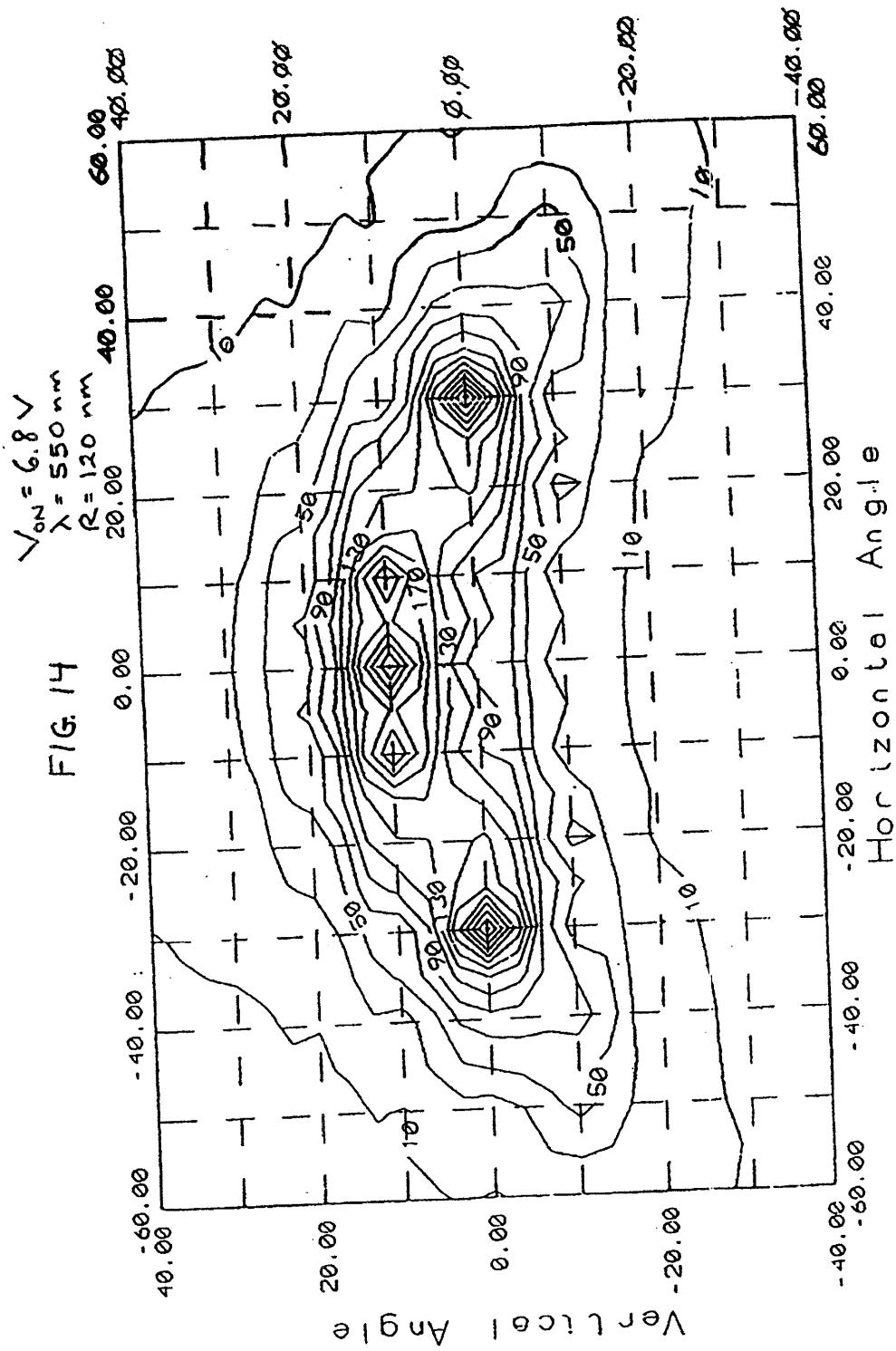


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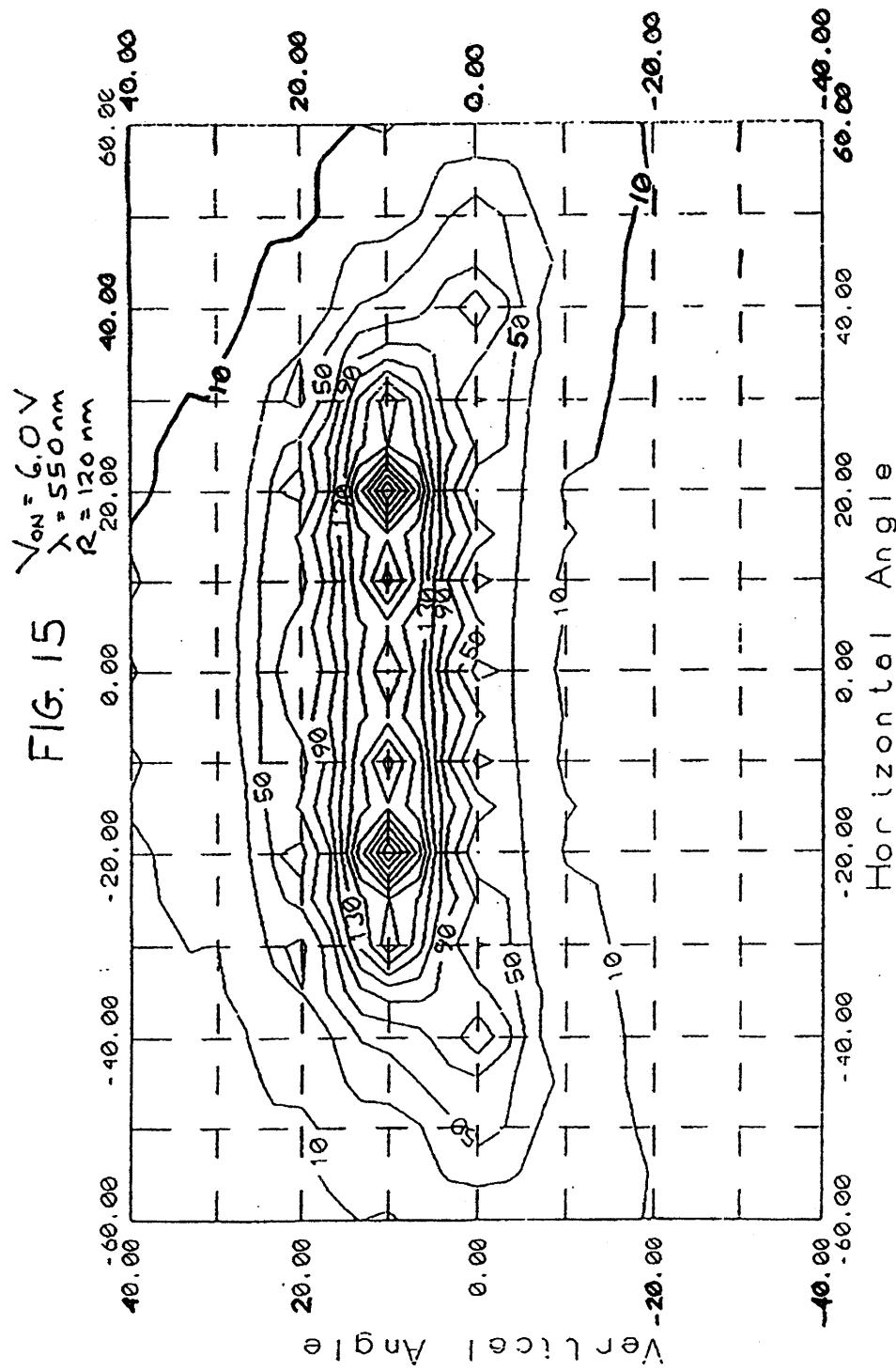


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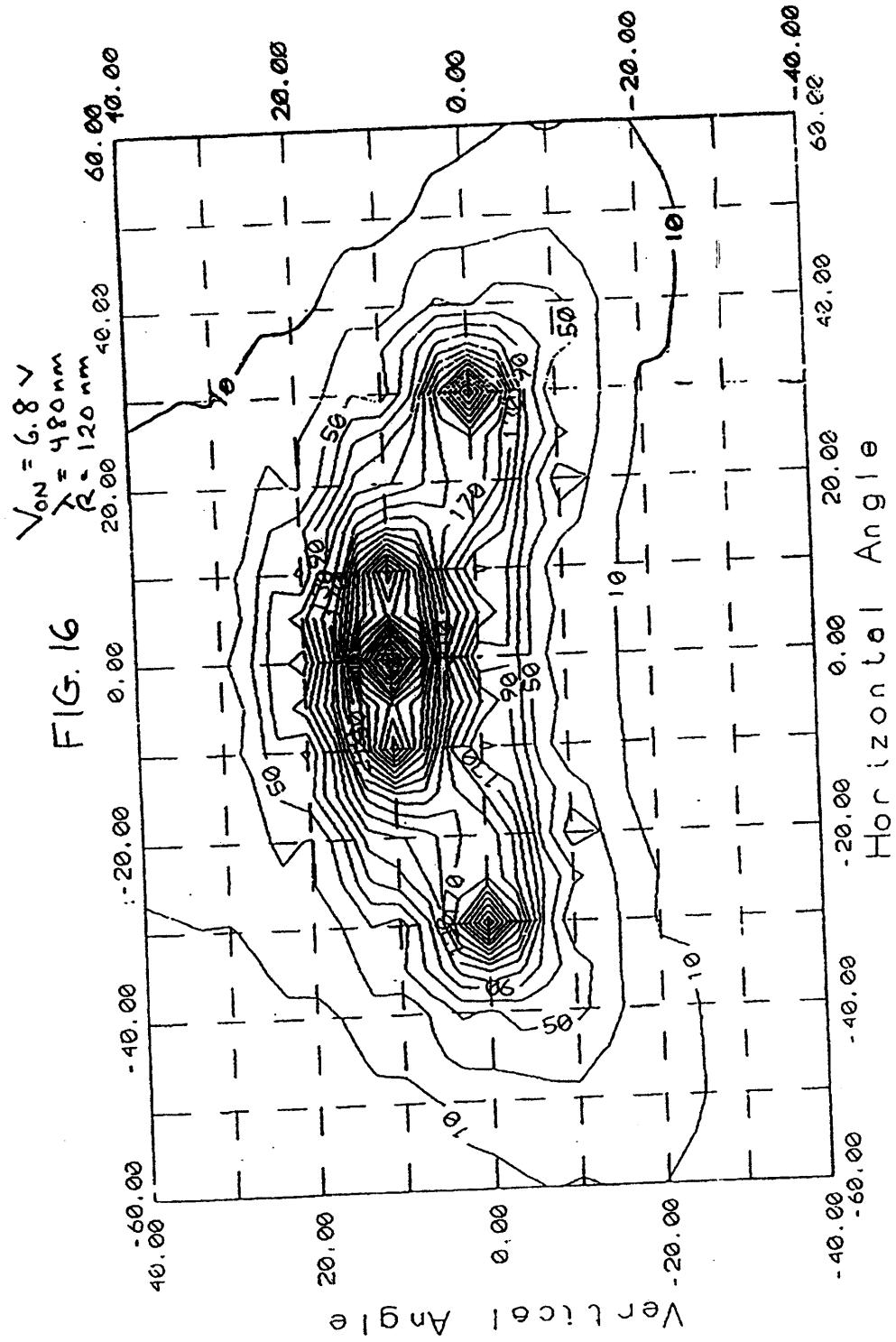


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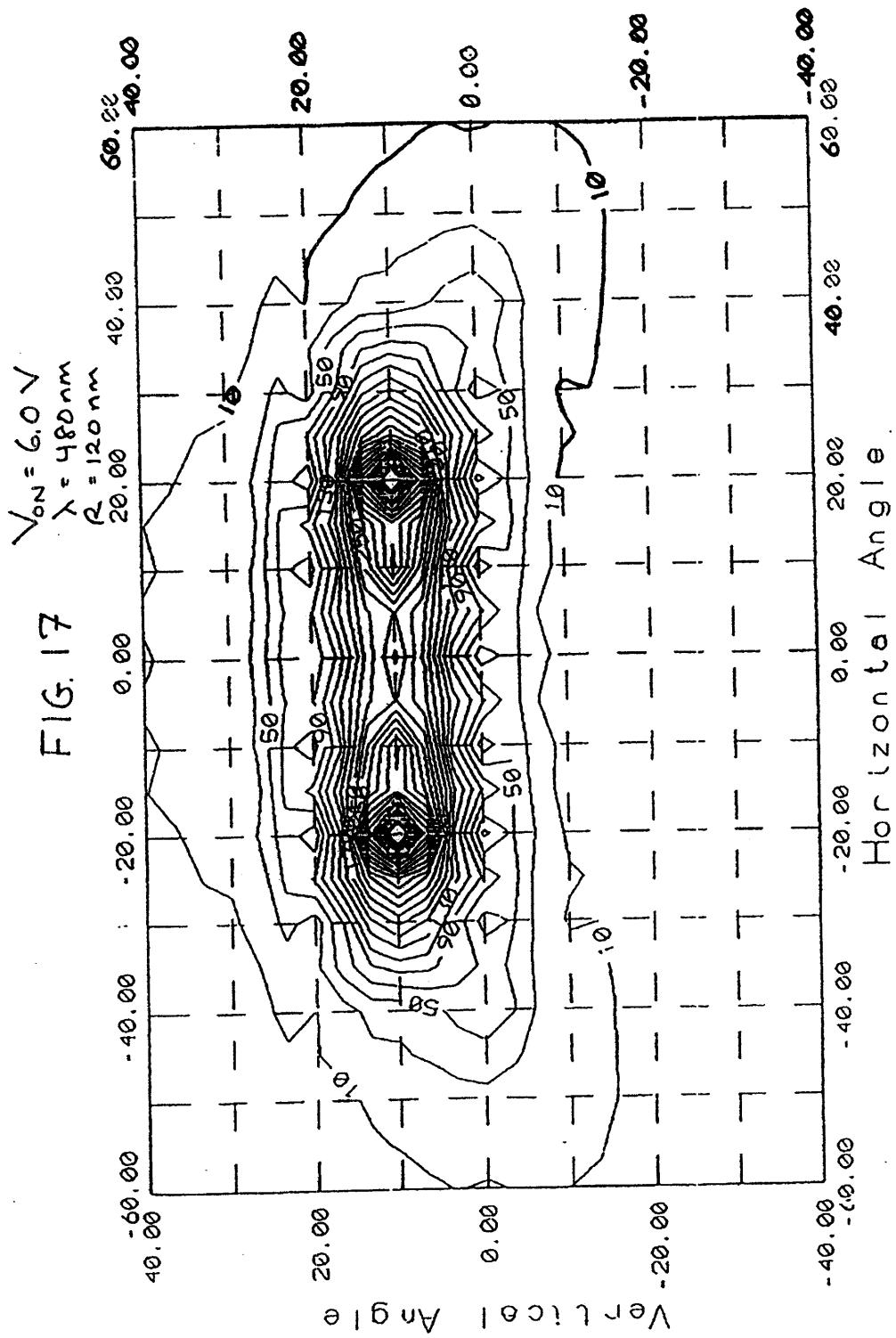


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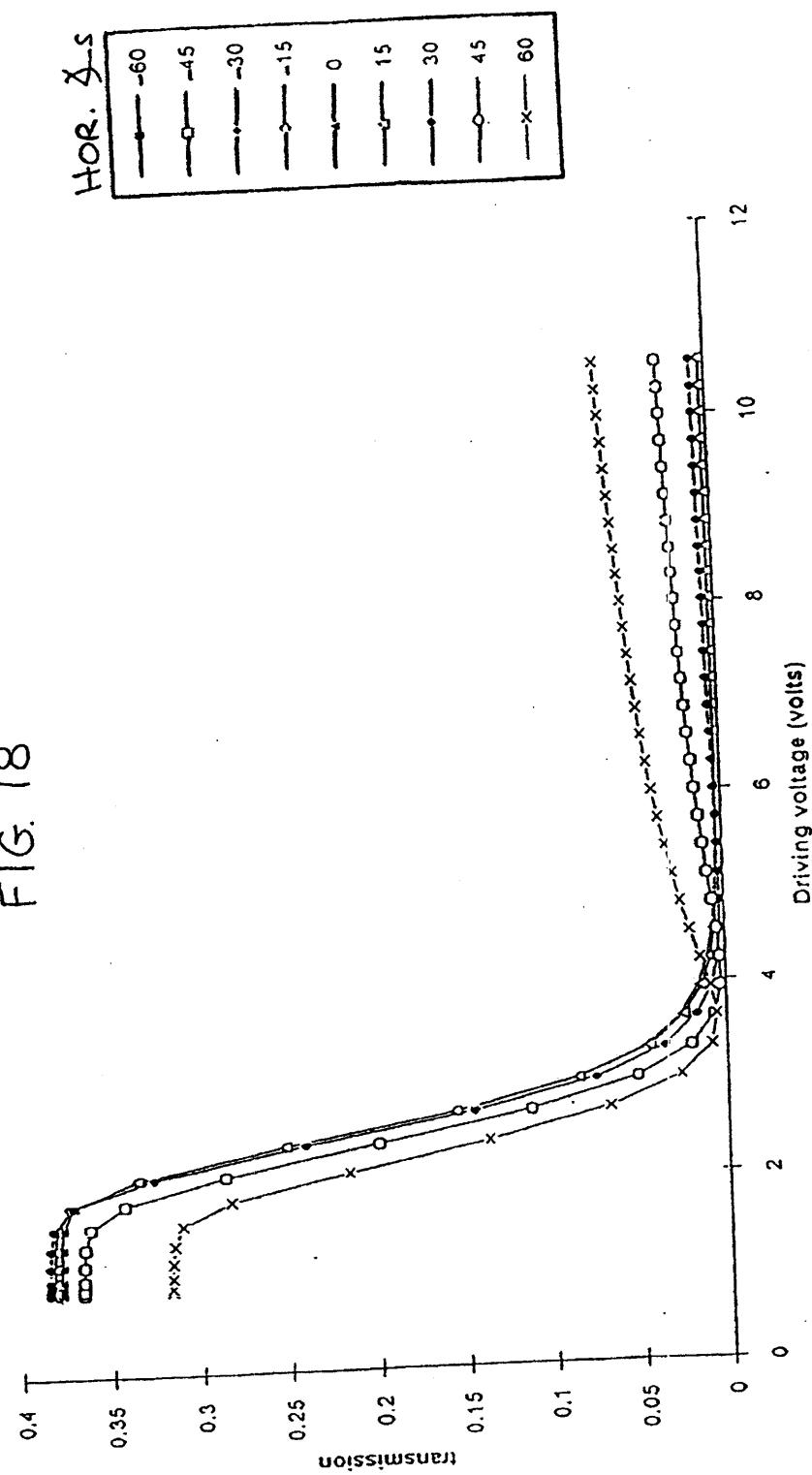


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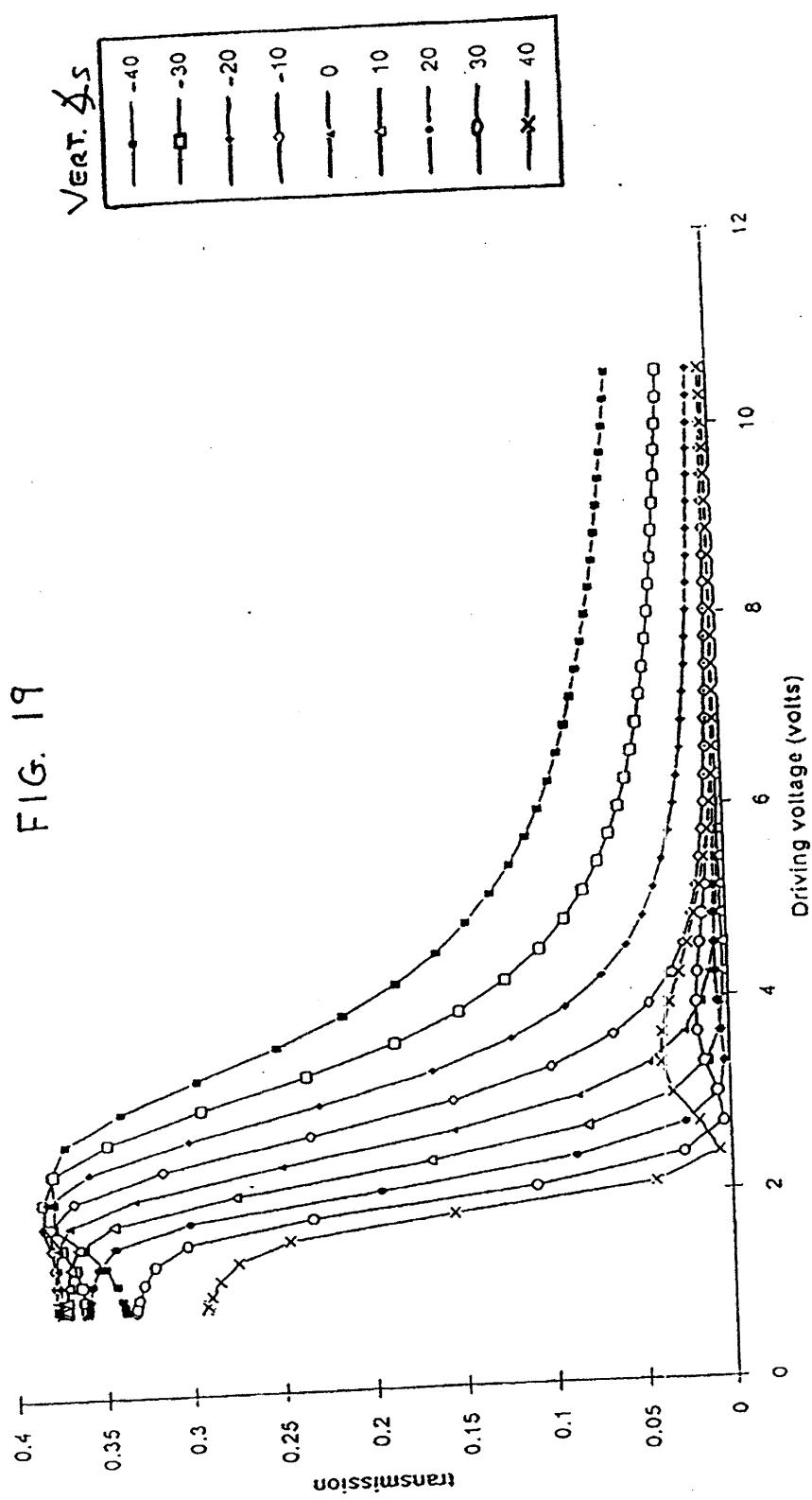


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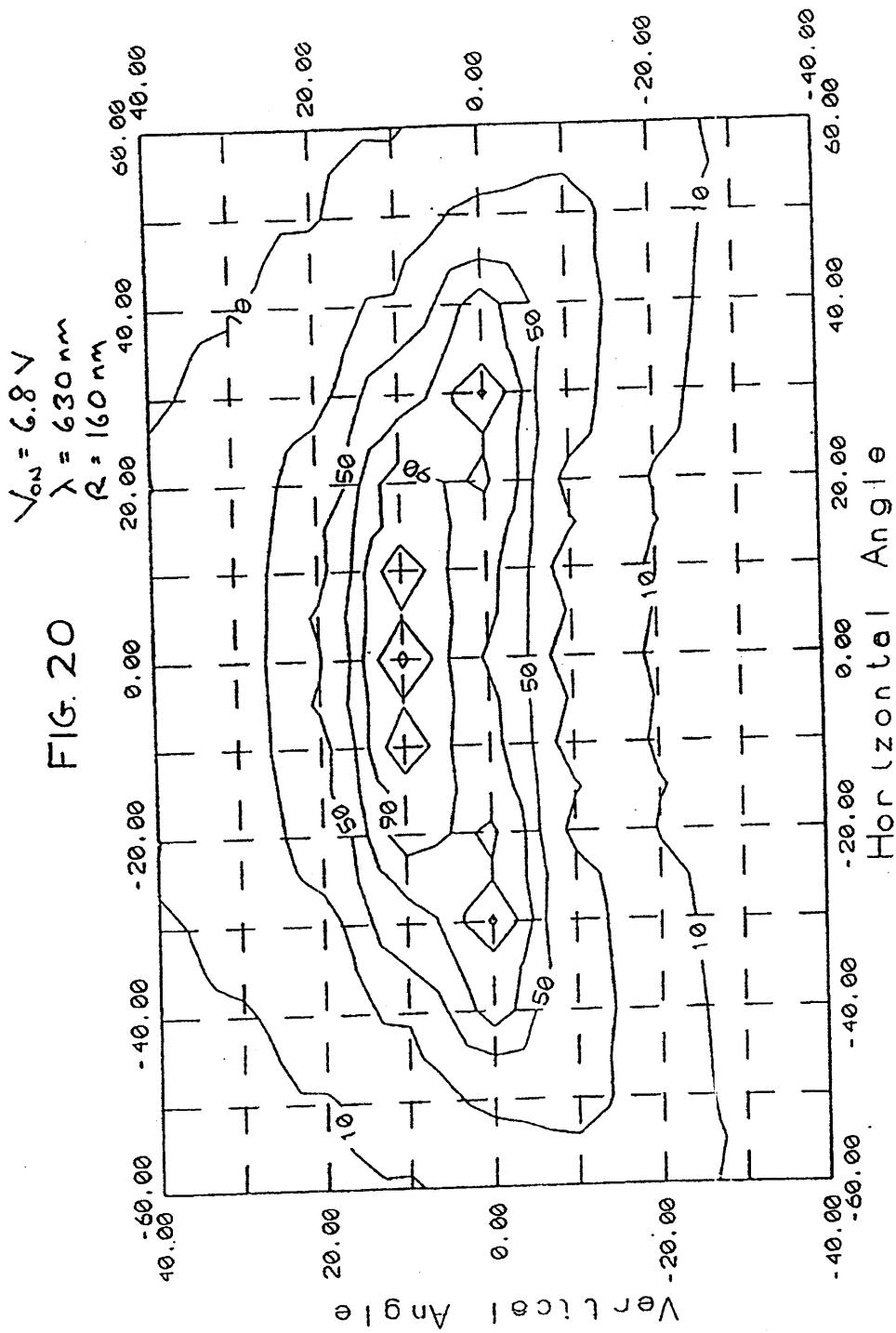


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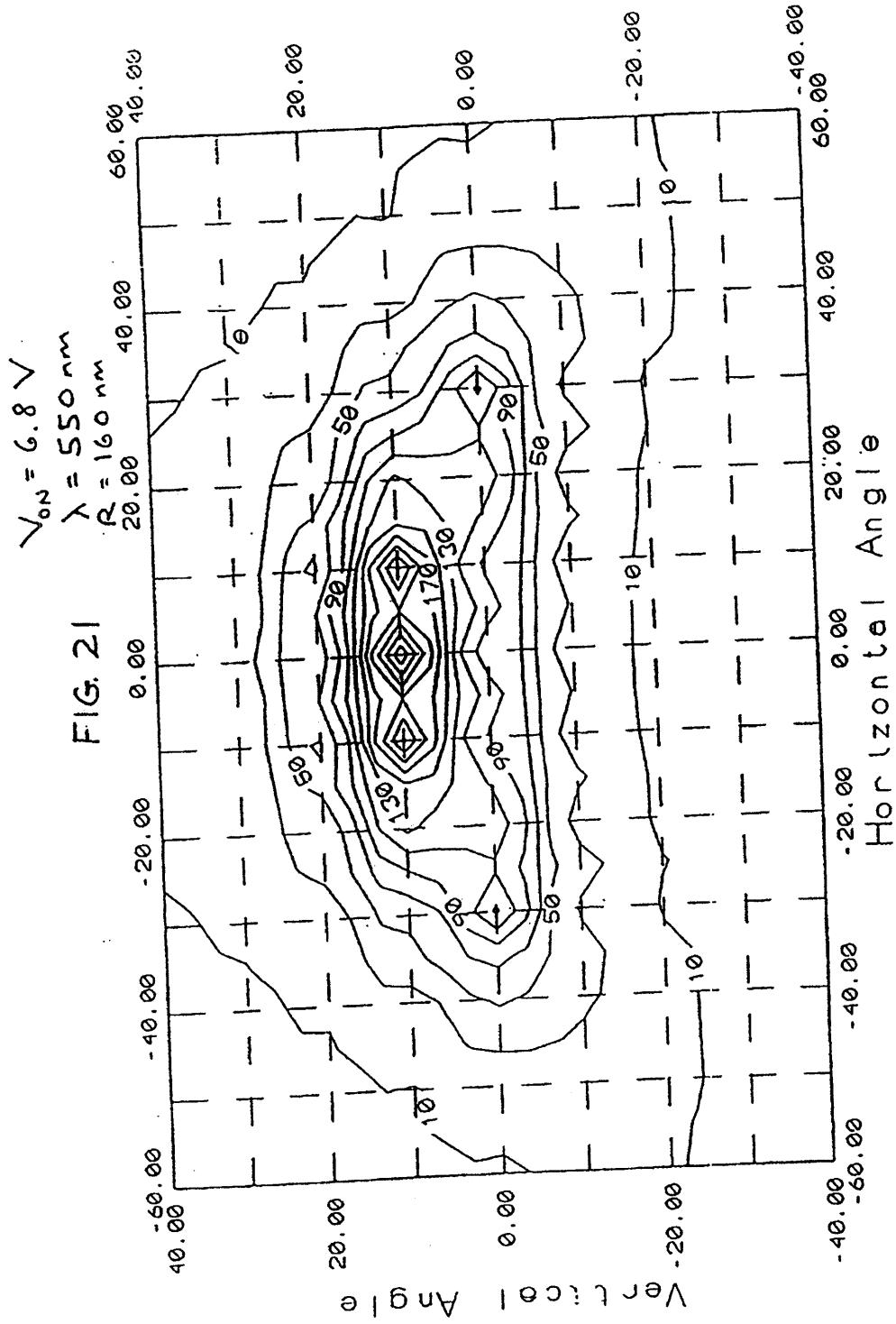


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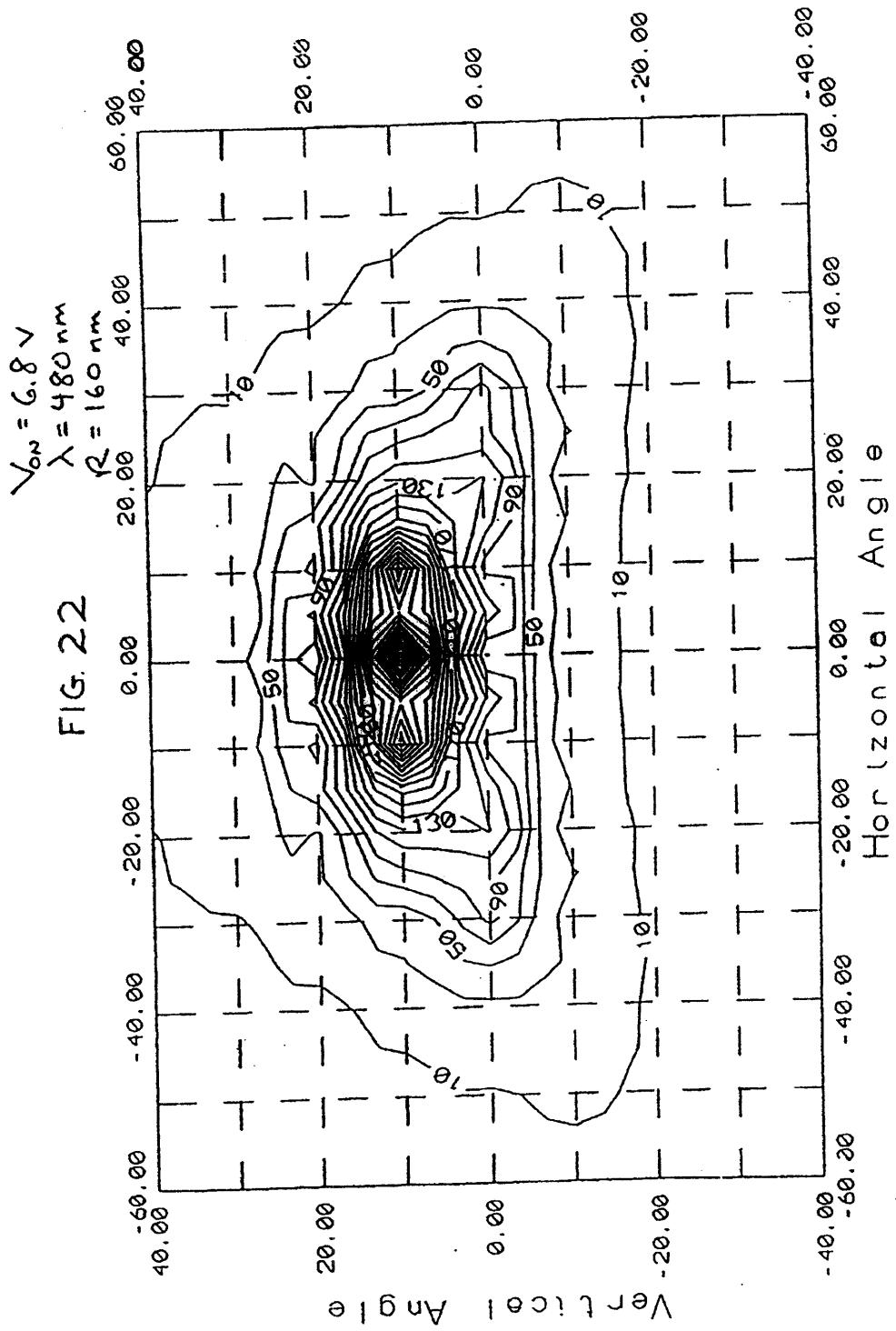


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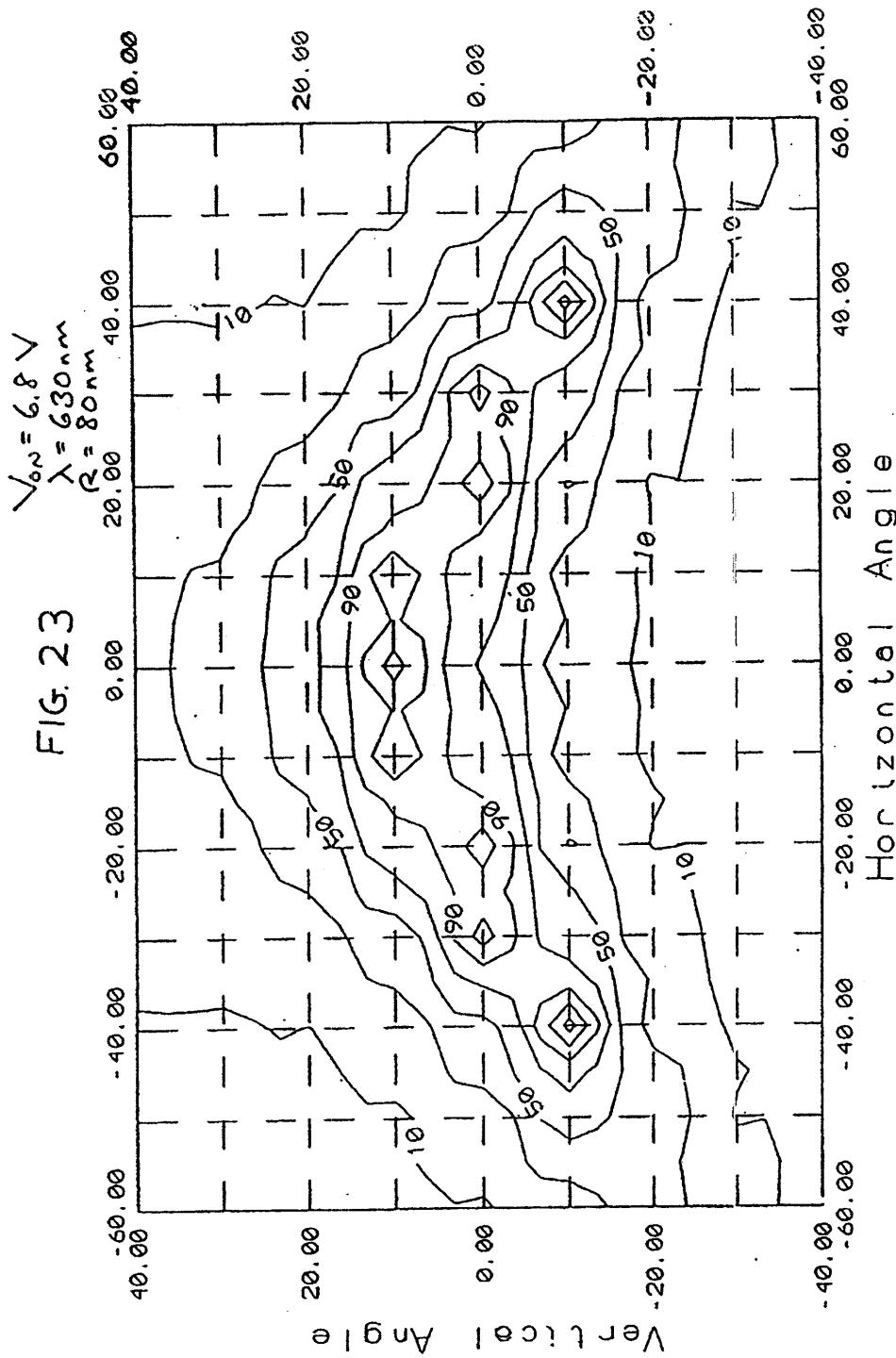


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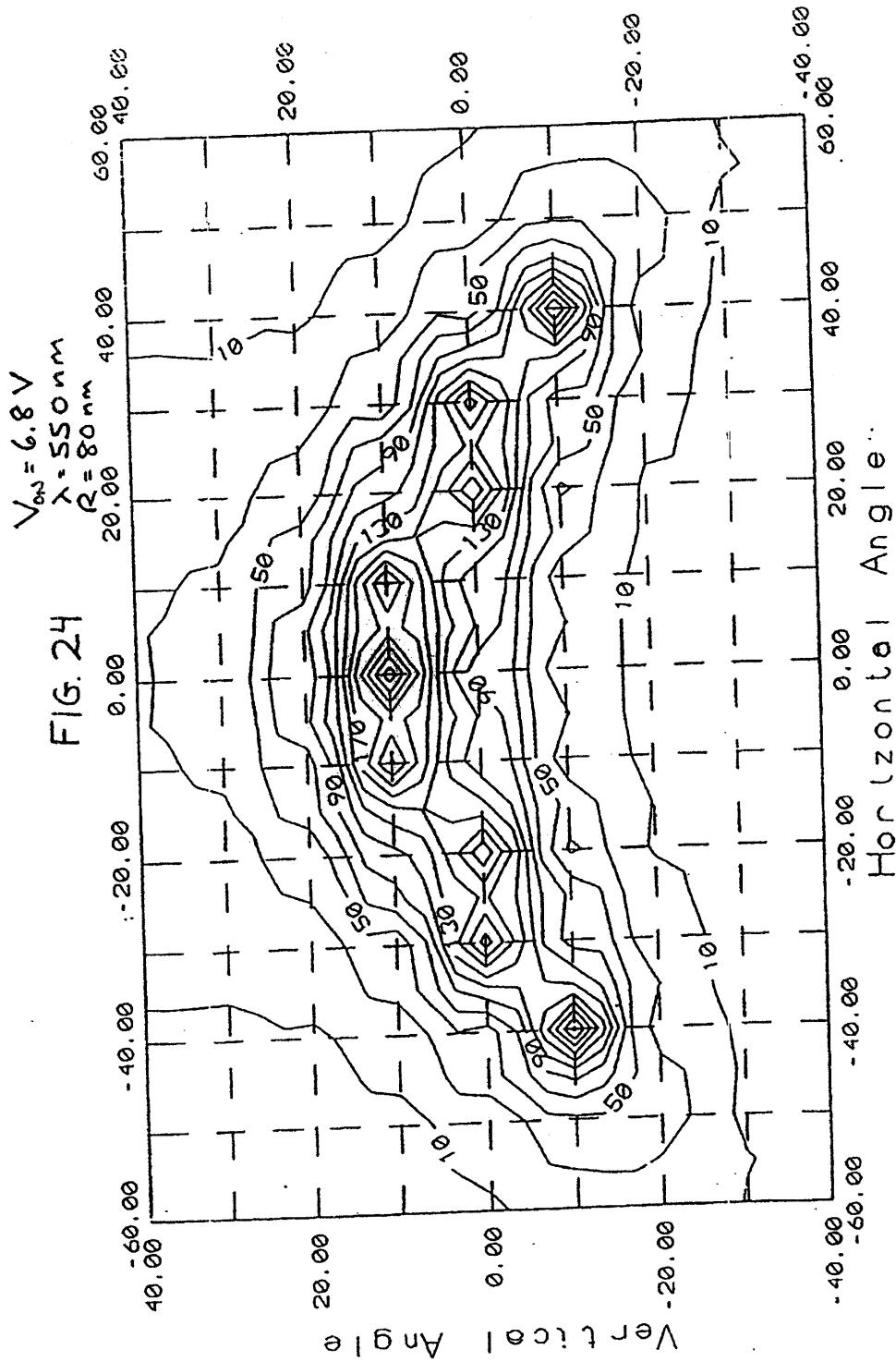


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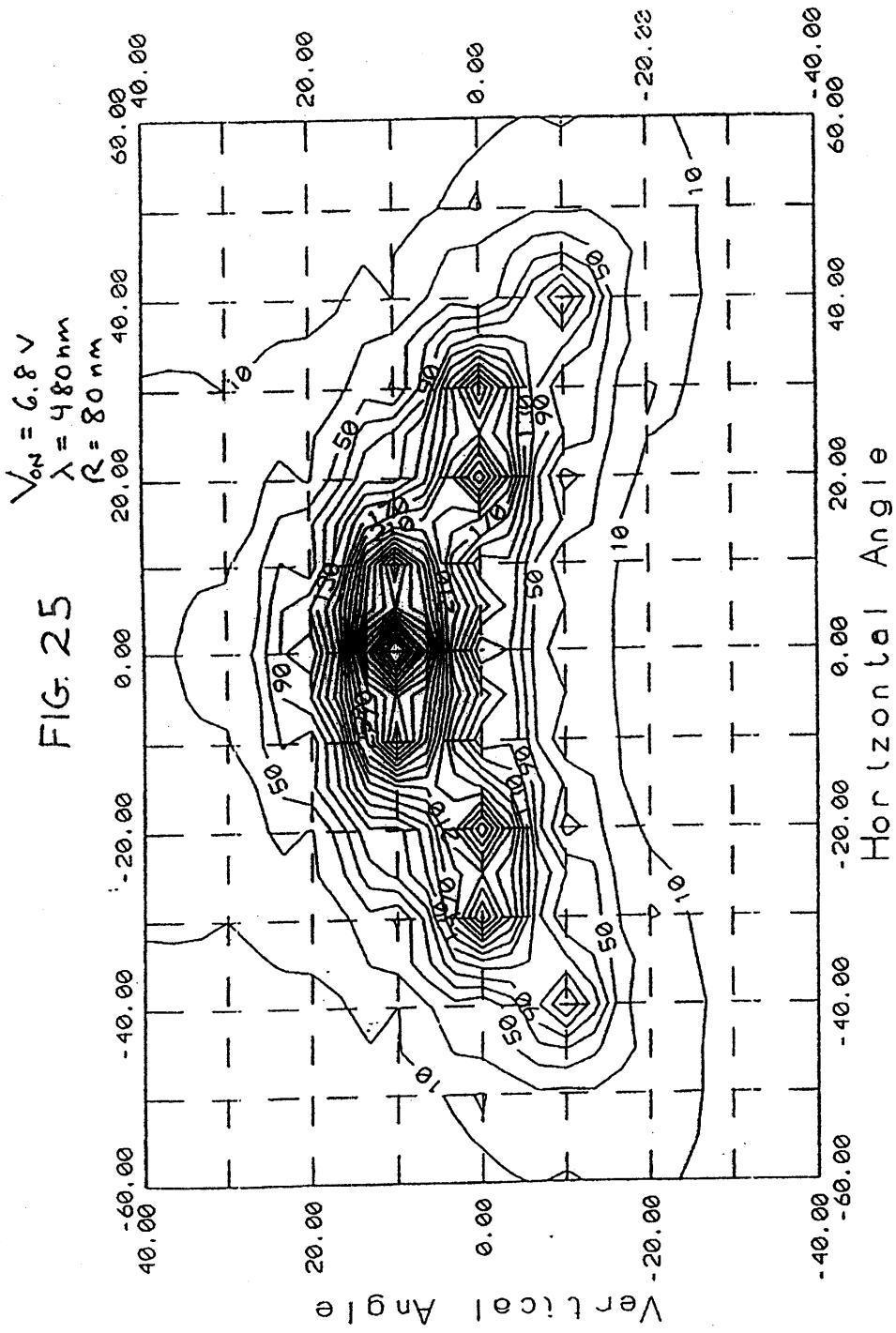


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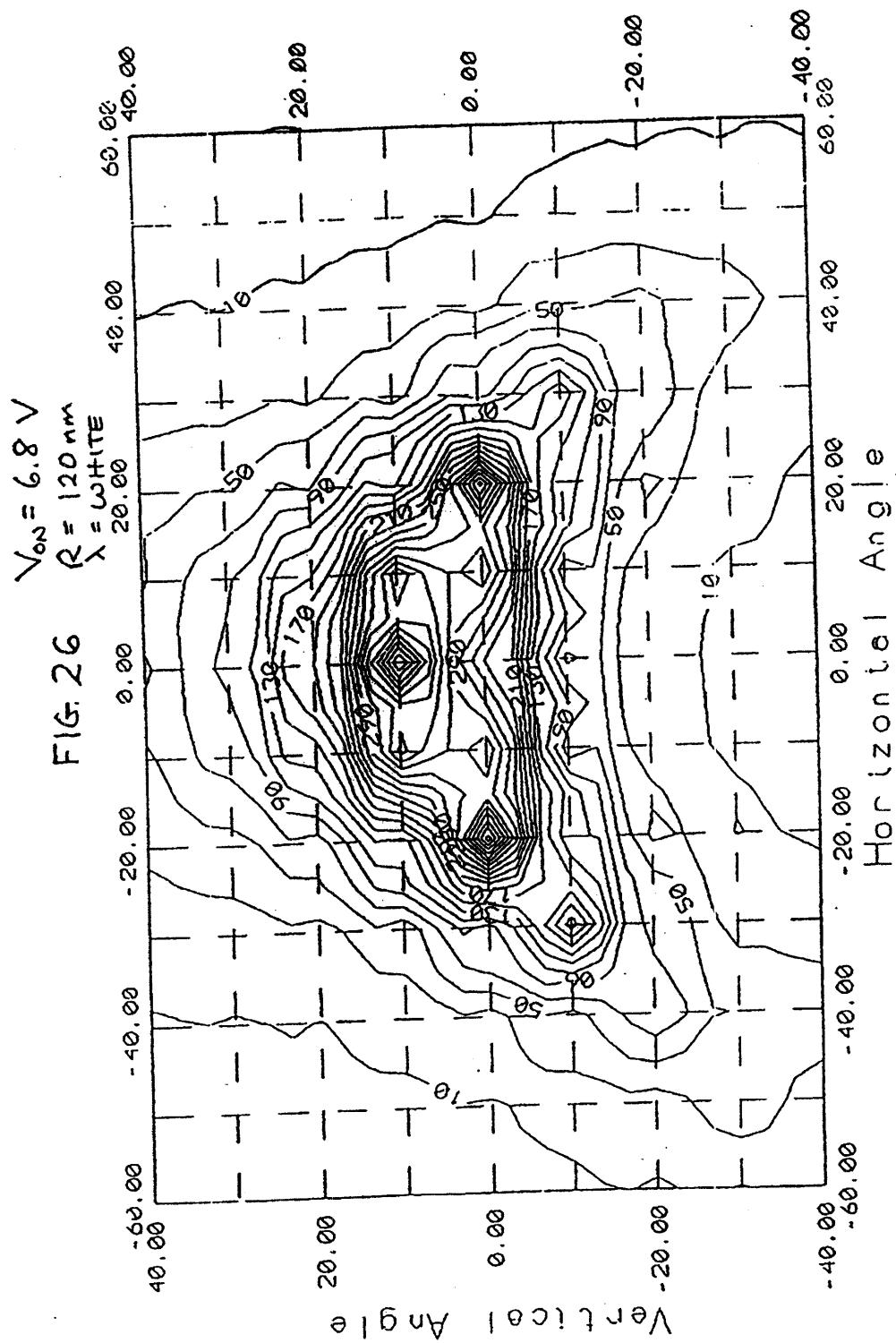


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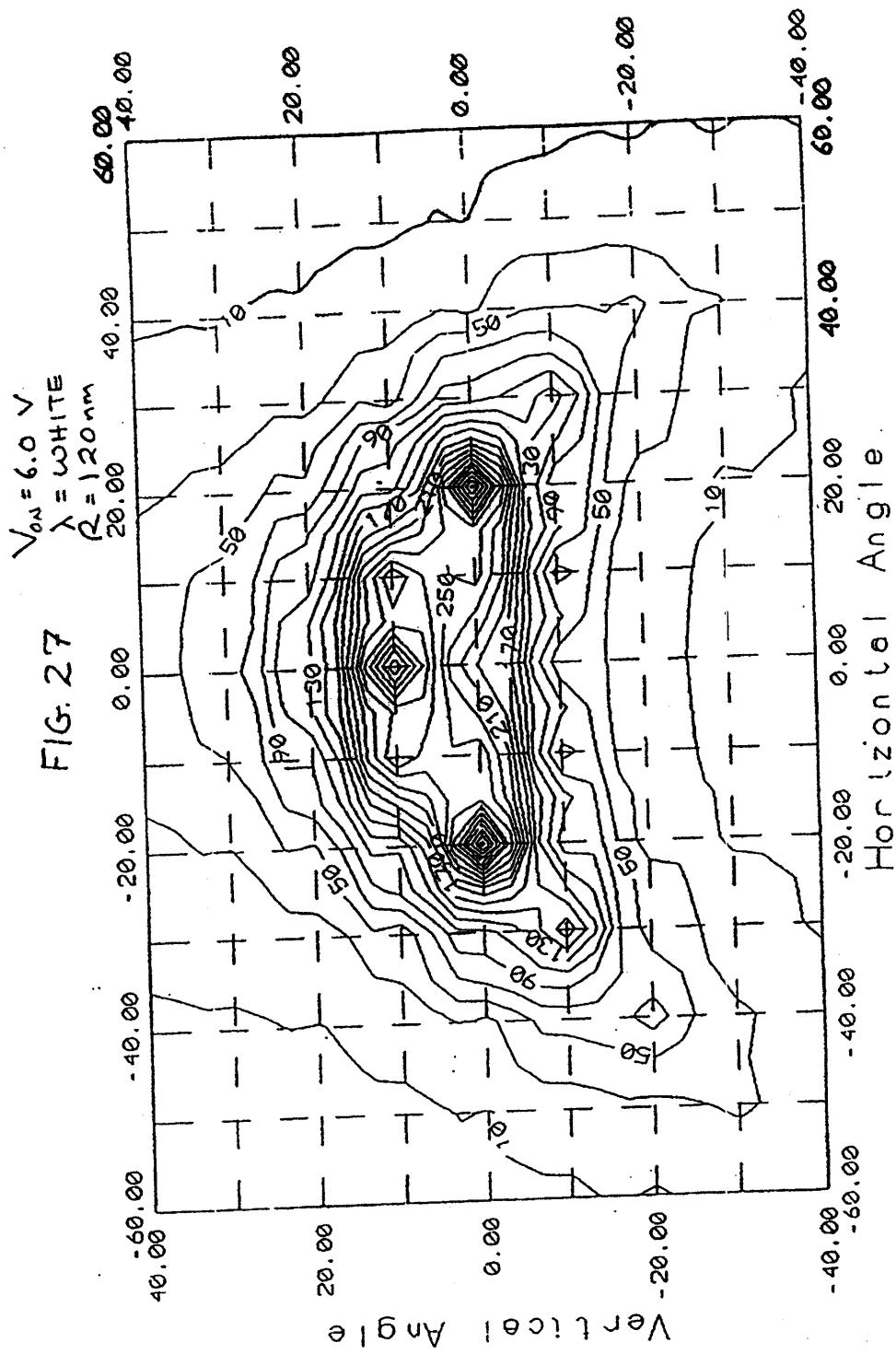


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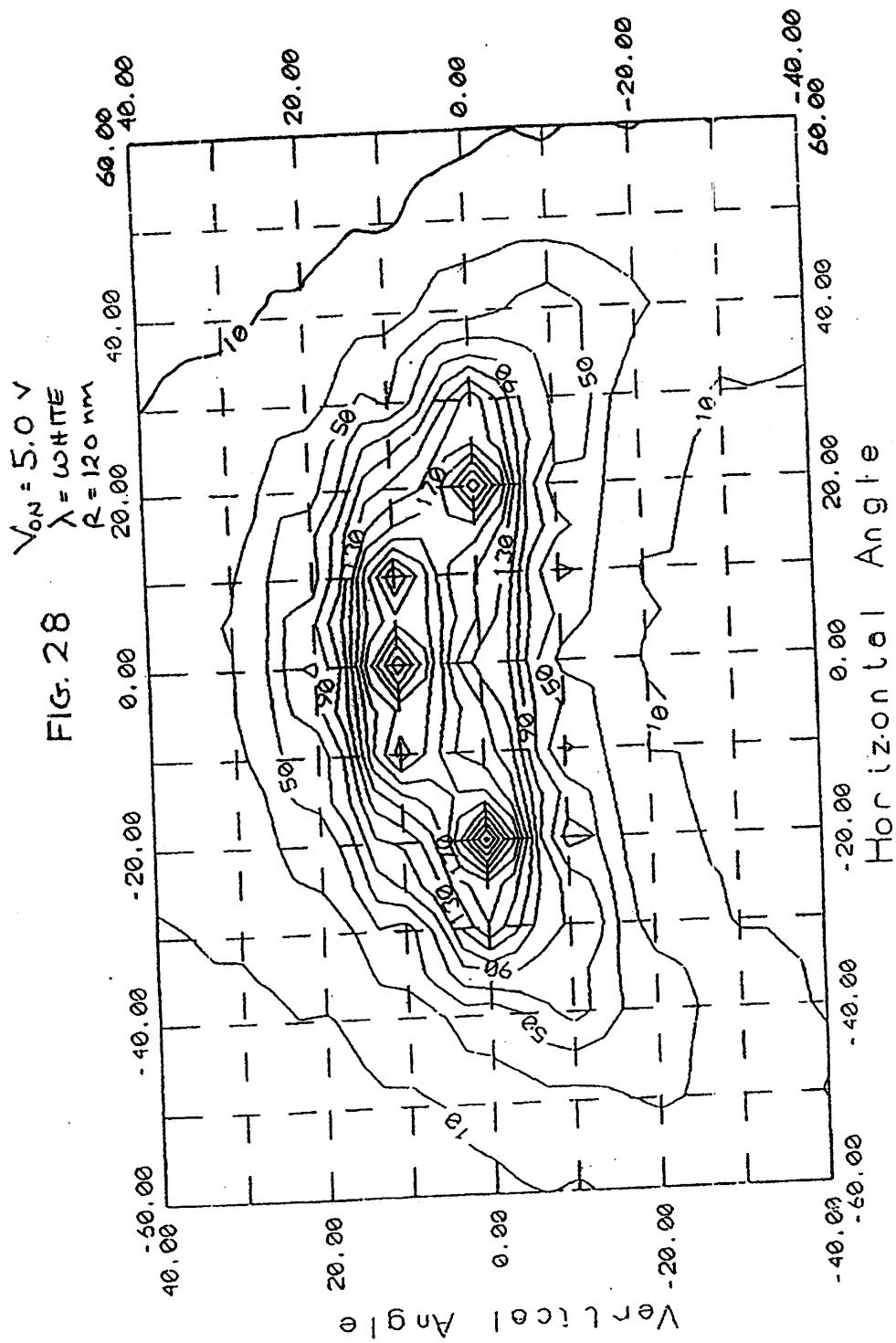


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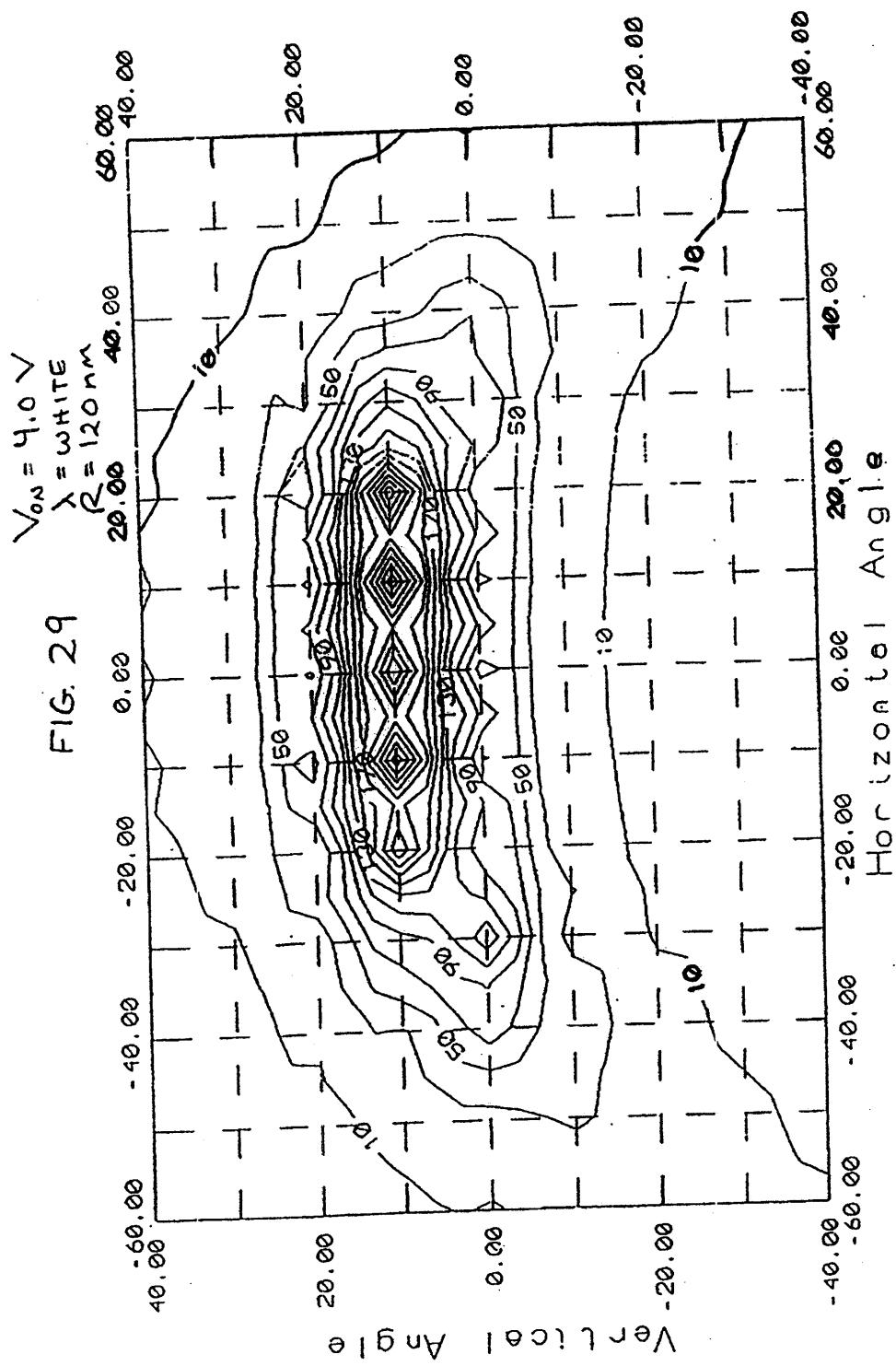


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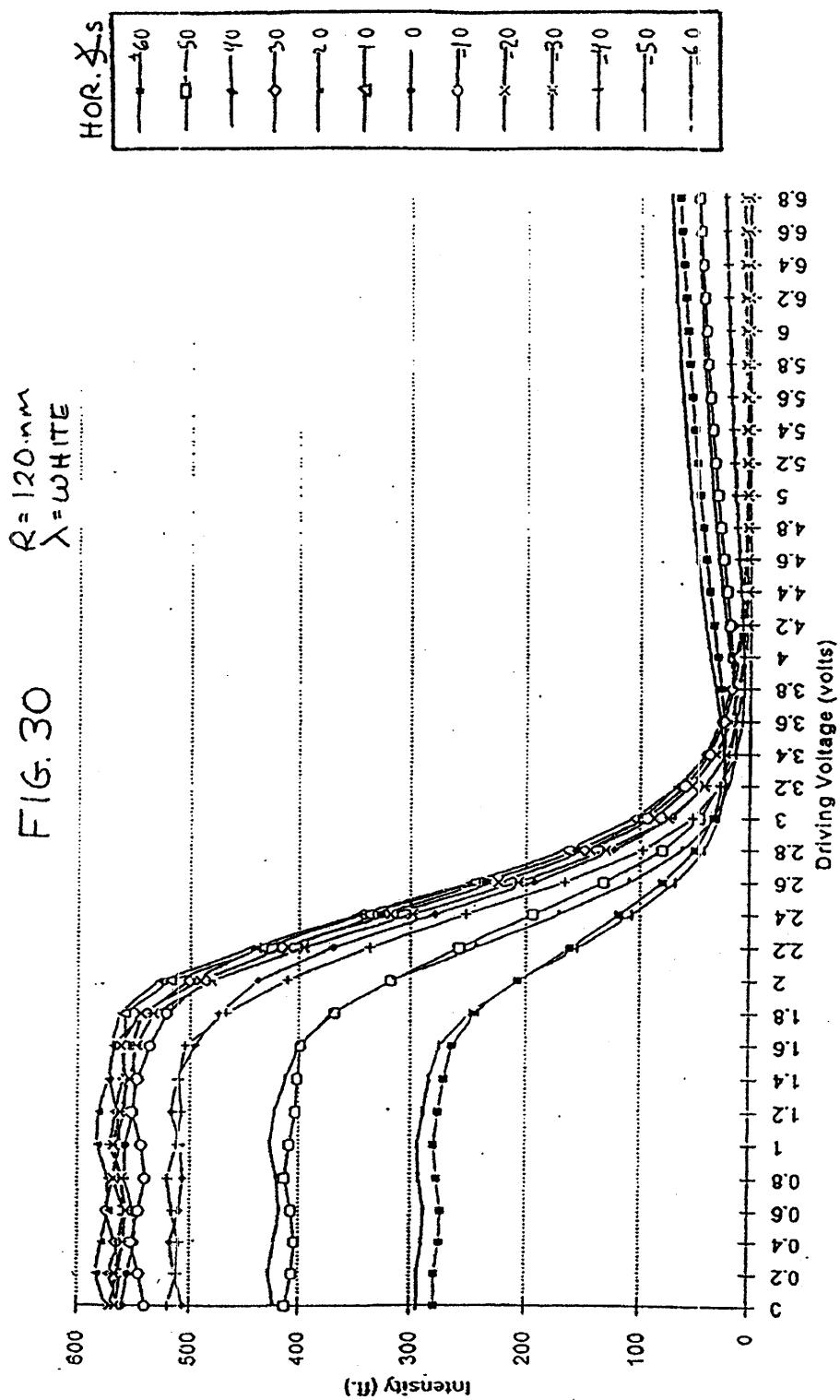


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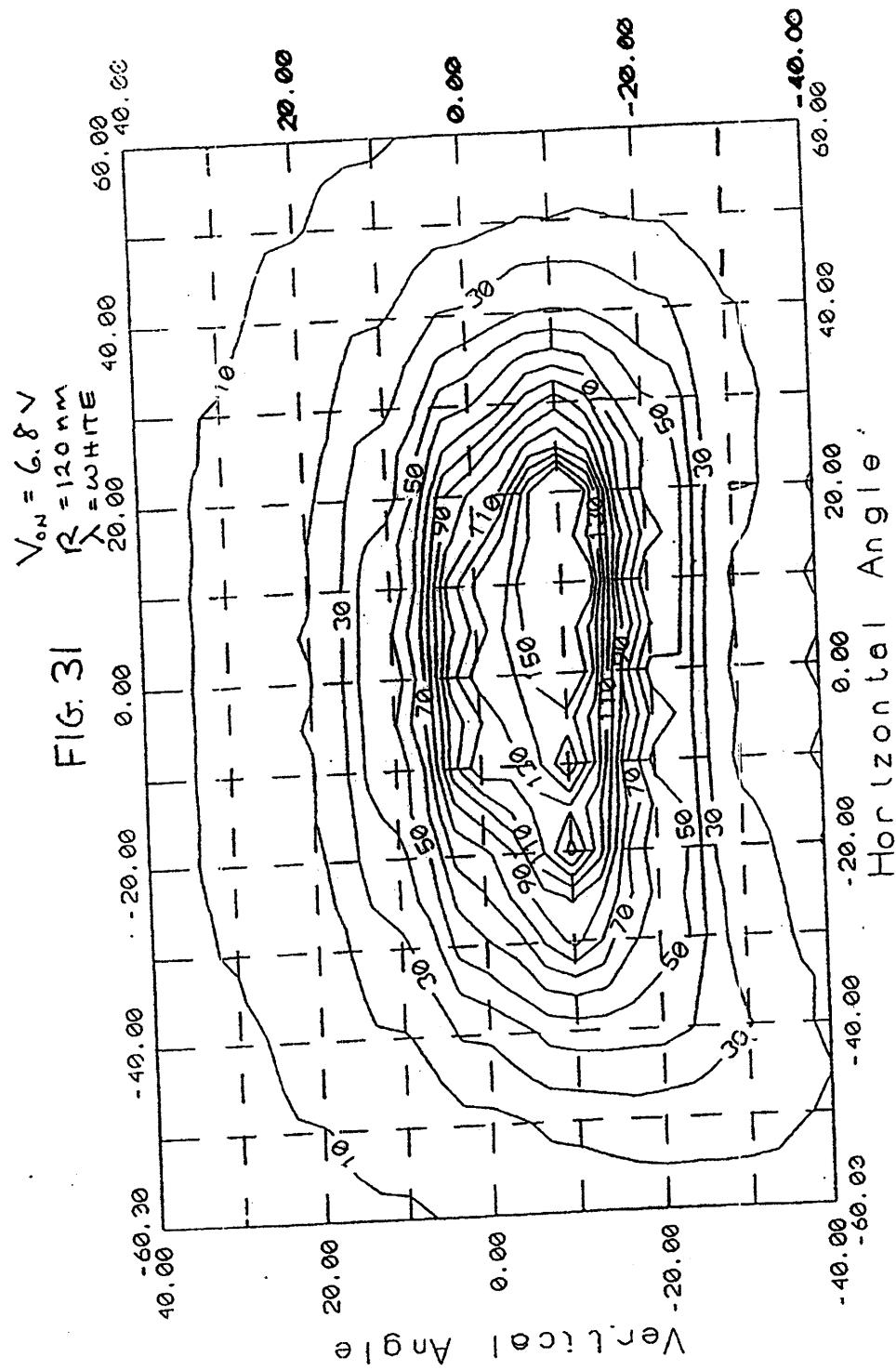


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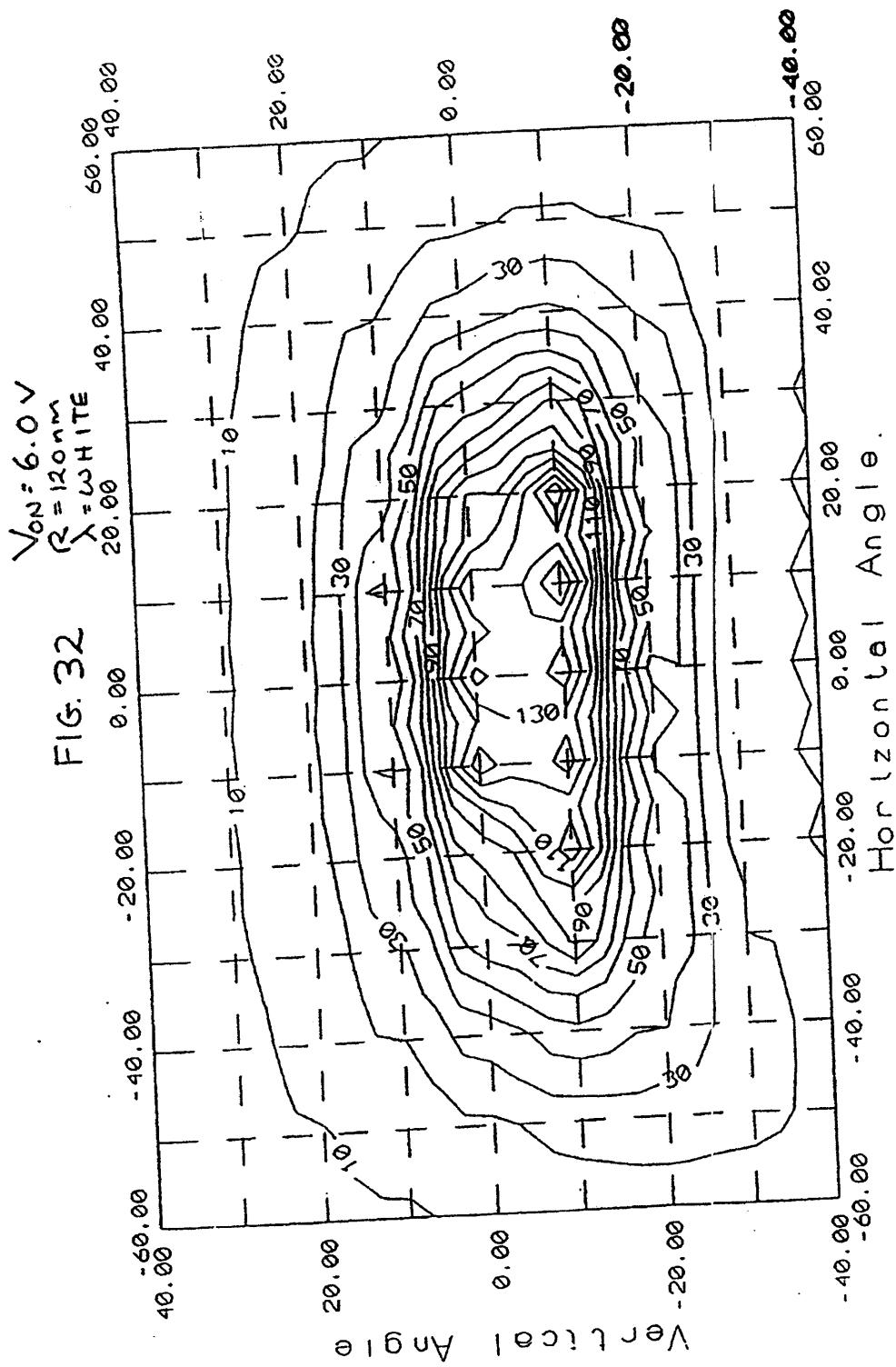


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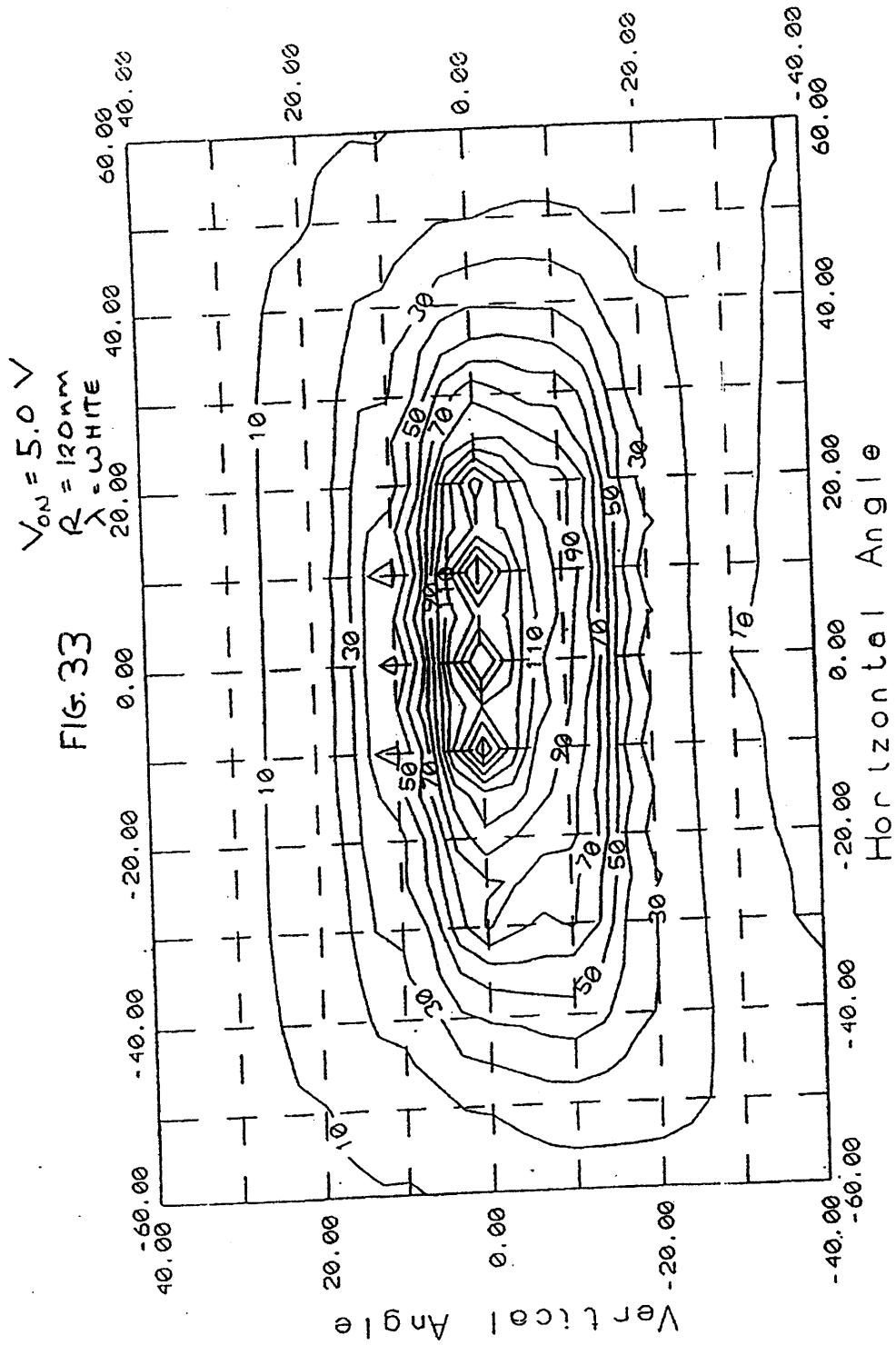


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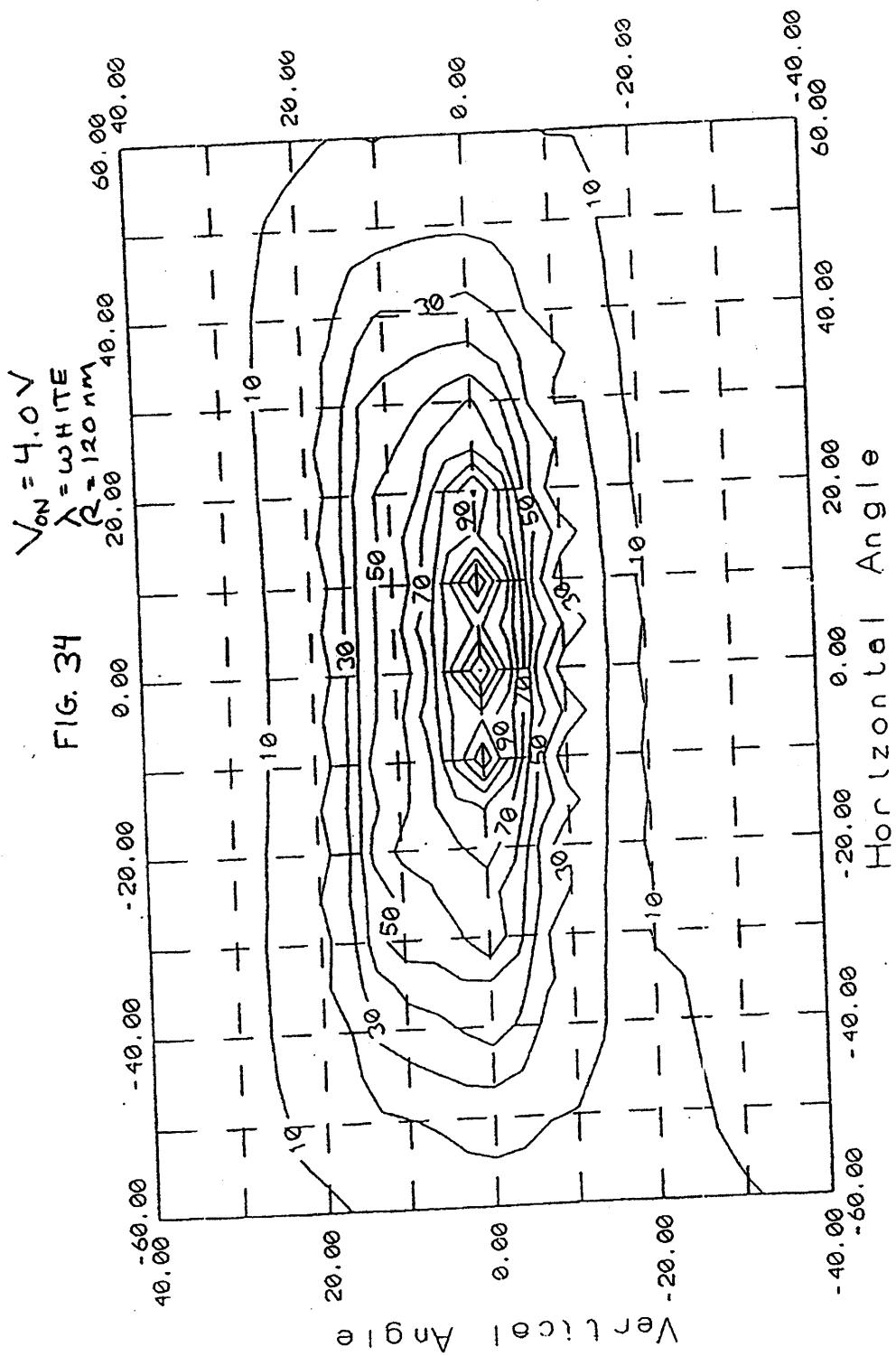


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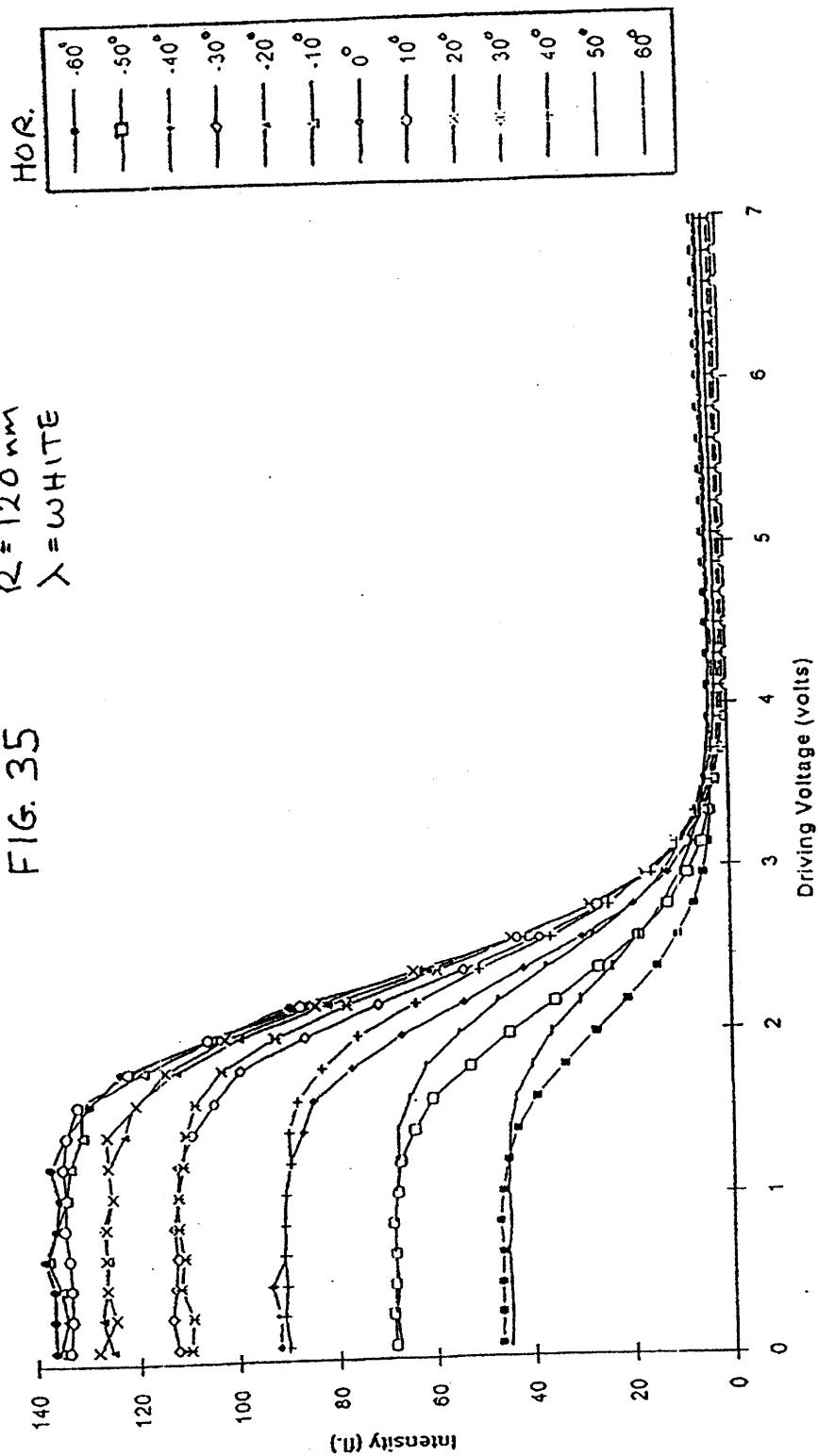


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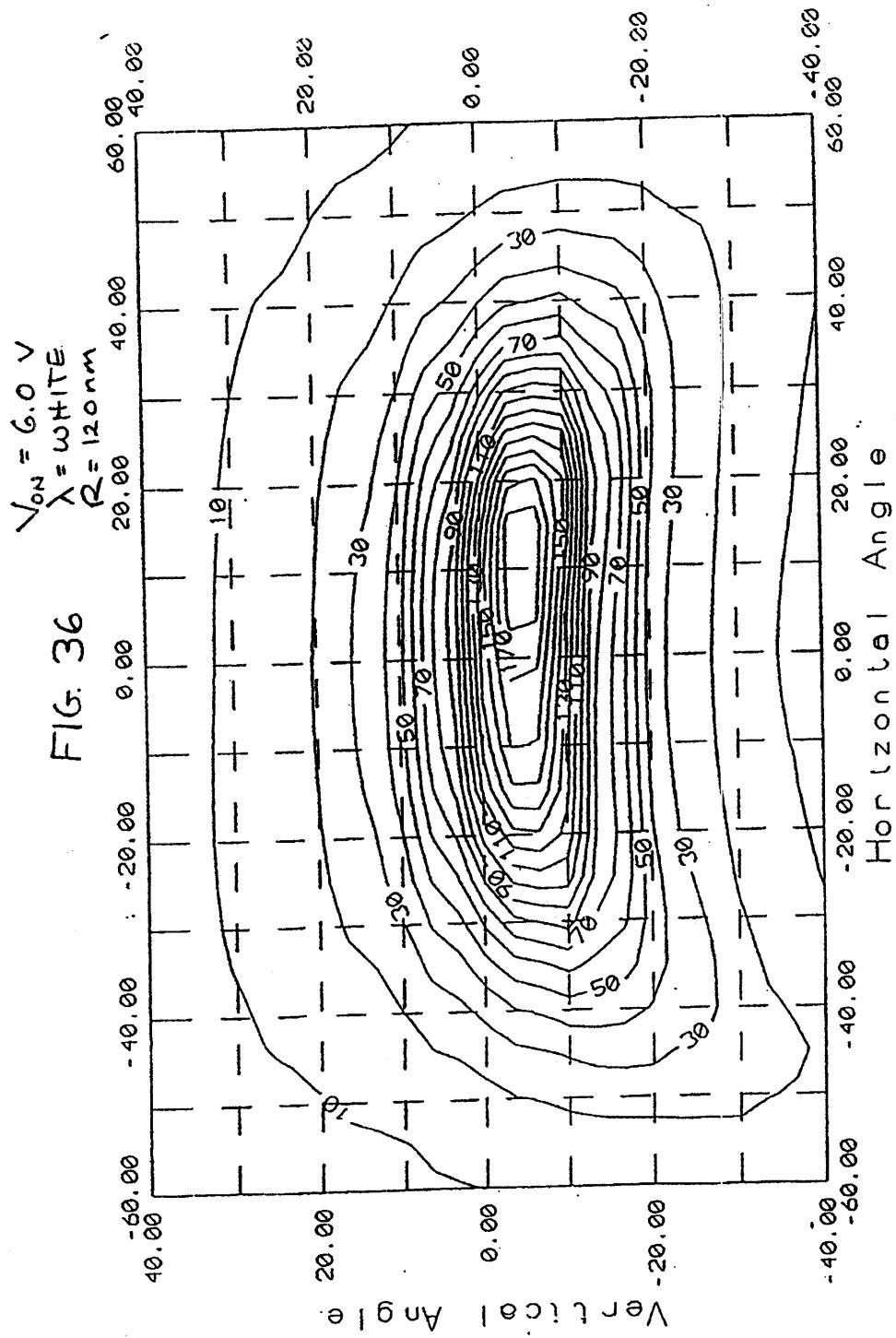


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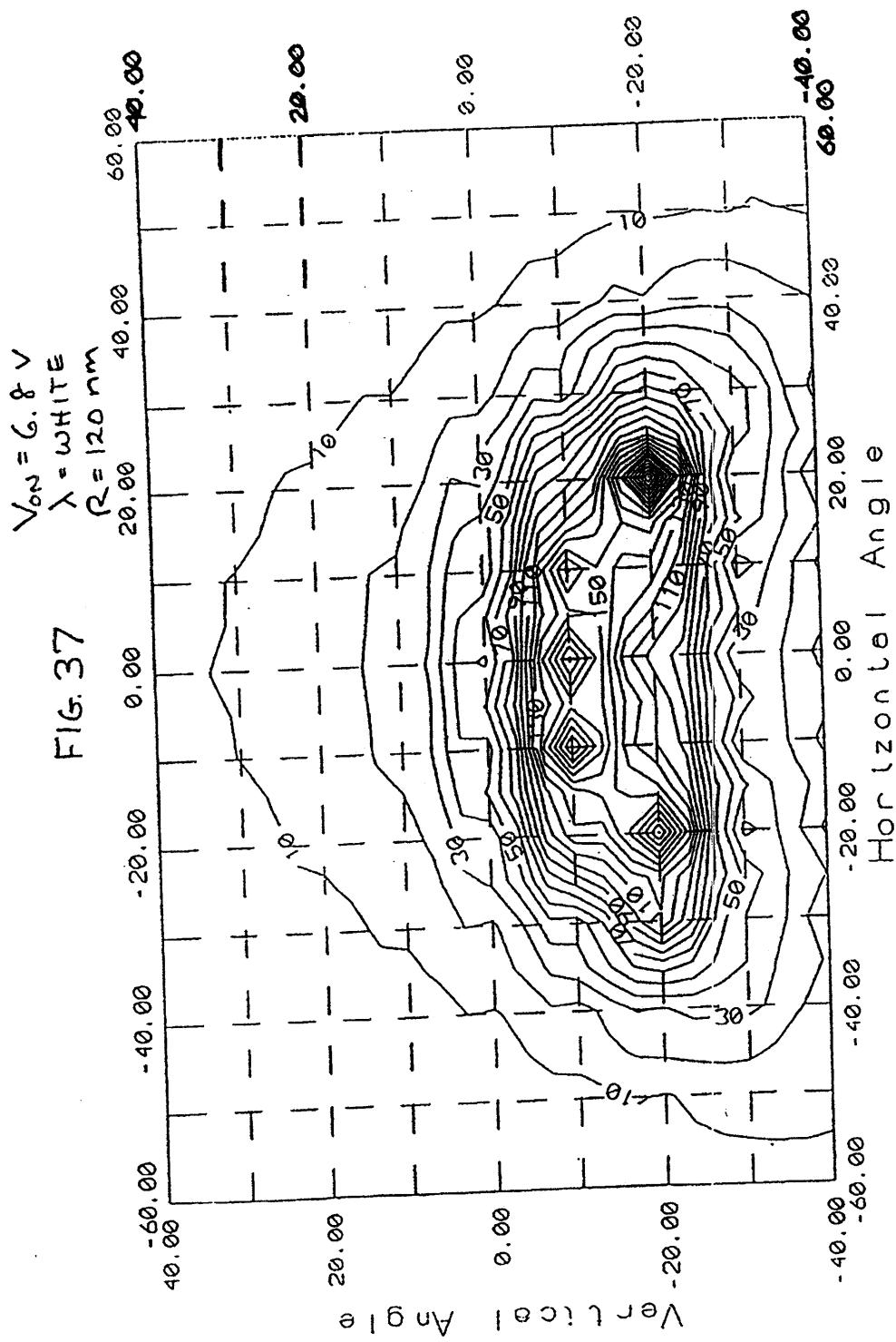


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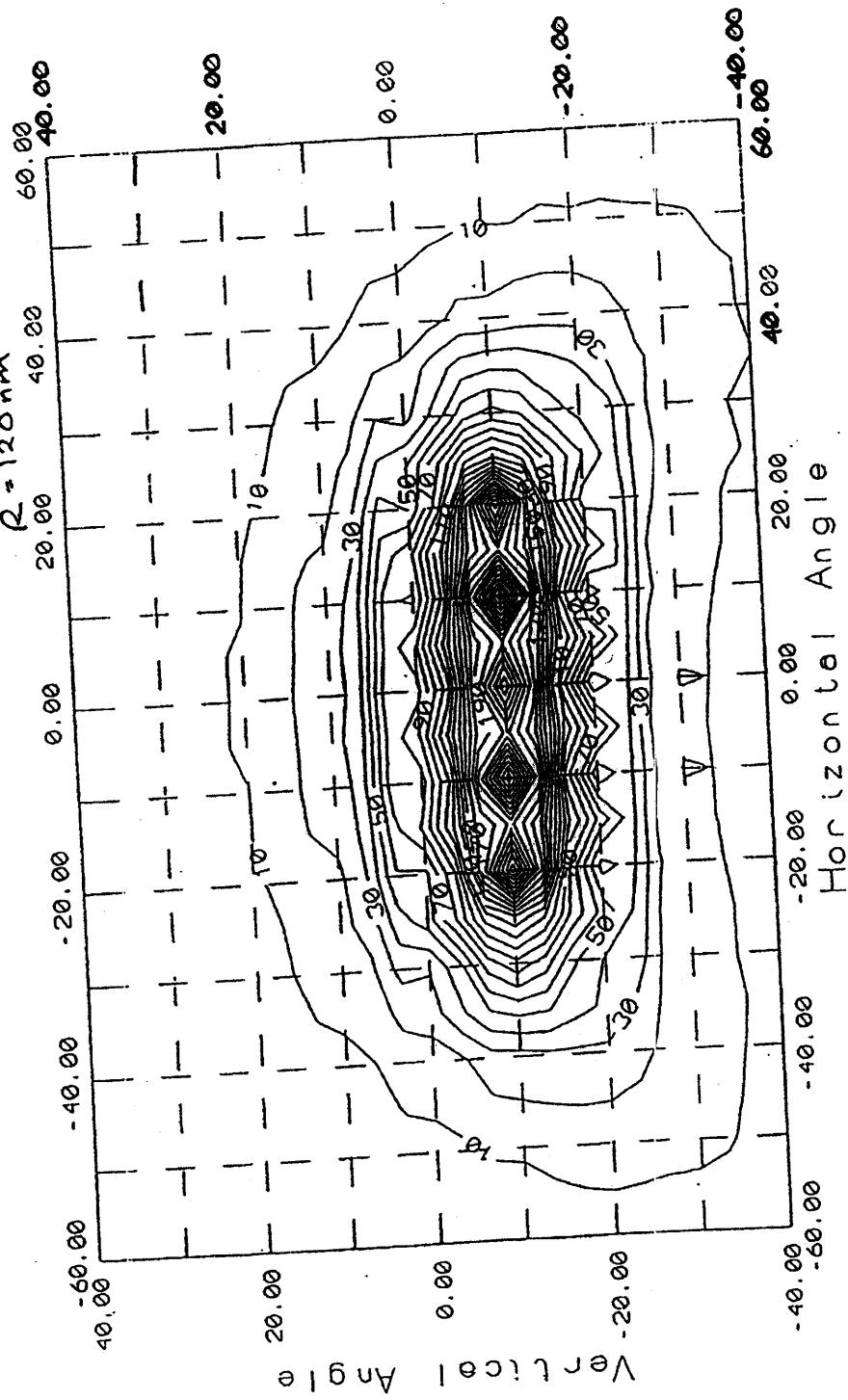
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 $V_{on} = 5.0 \text{ V}$ $\lambda = \text{WHITE}$ $Q = 12.0 \text{ nm}$

FIG. 38A

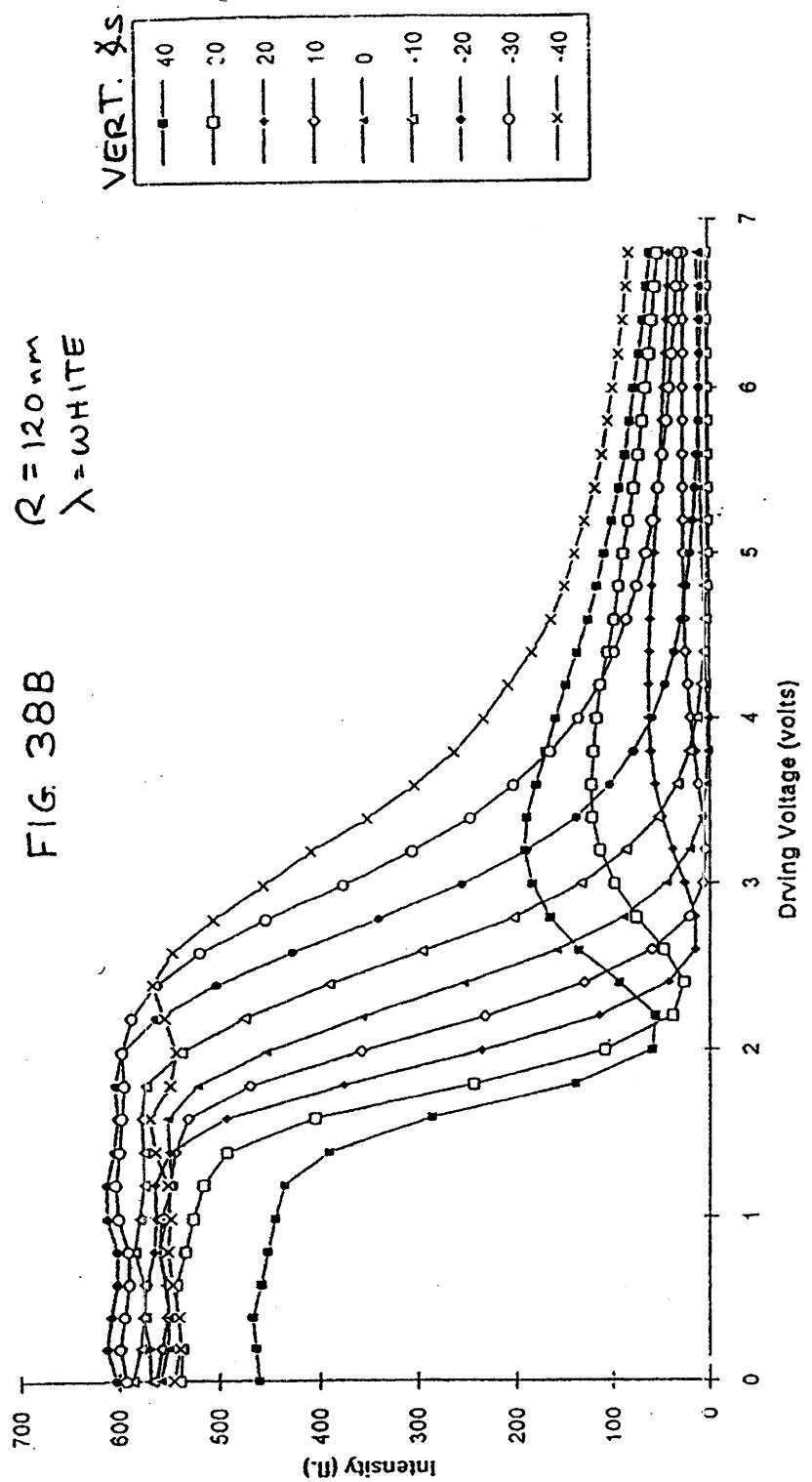


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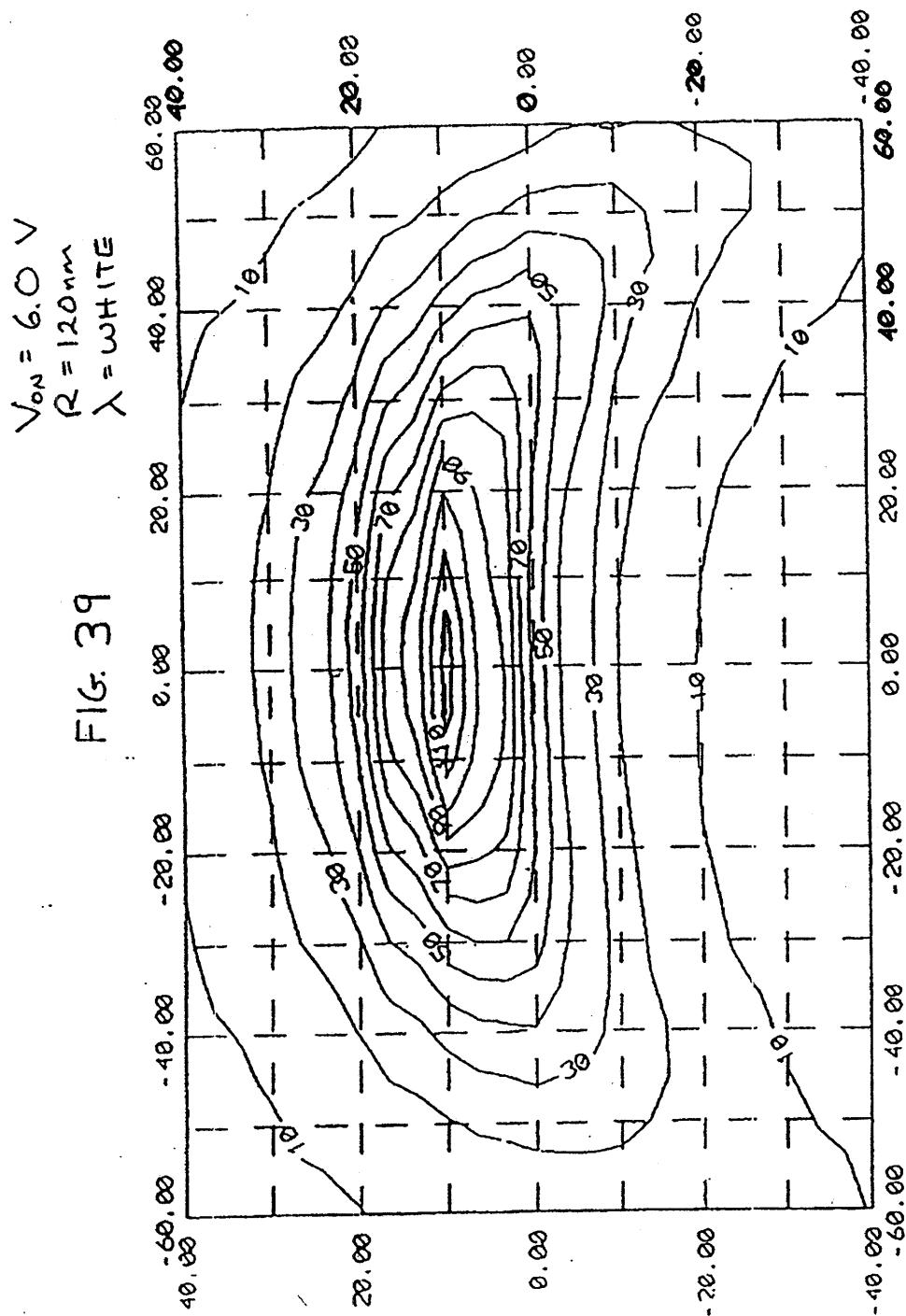


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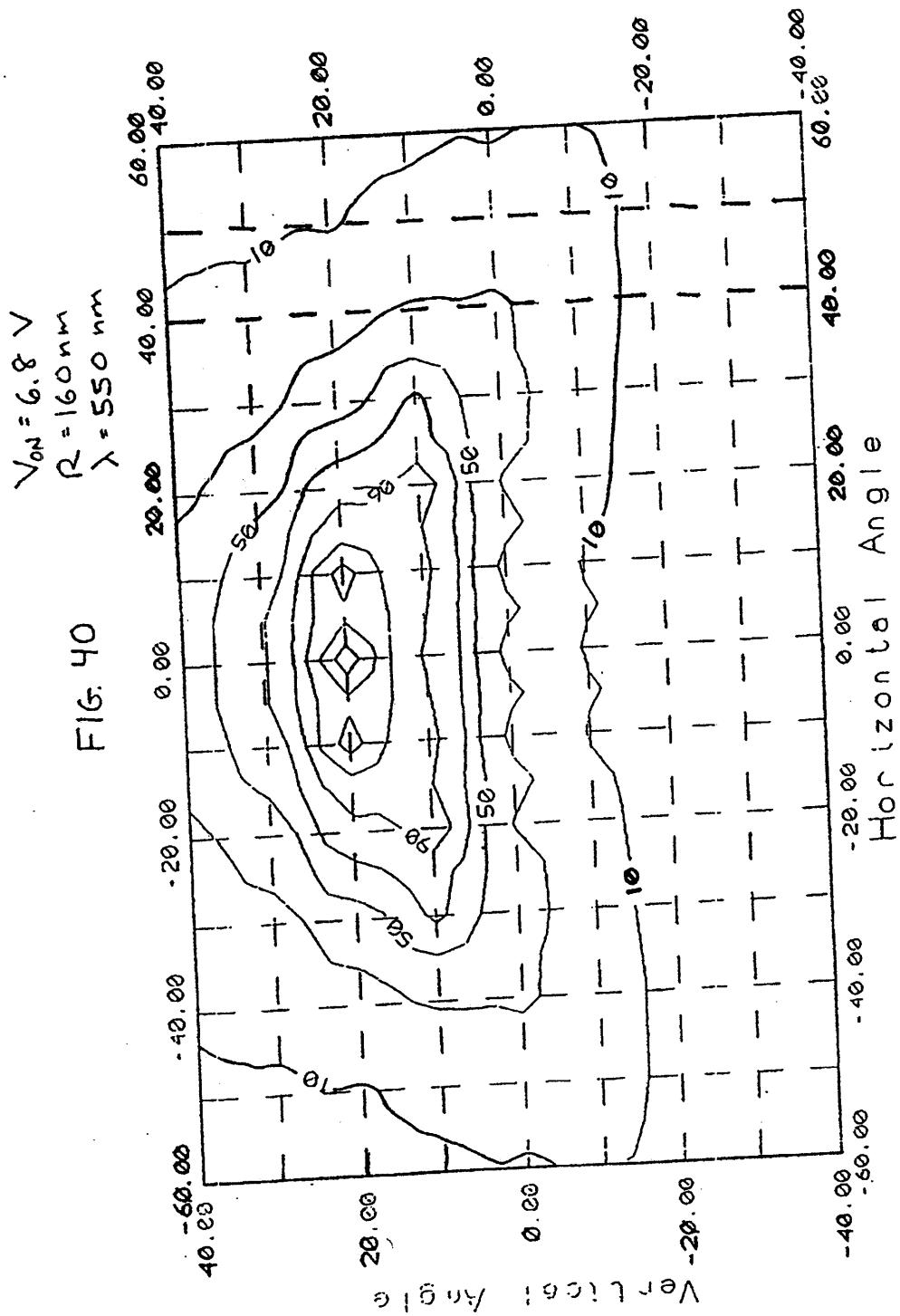


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Fig. 42

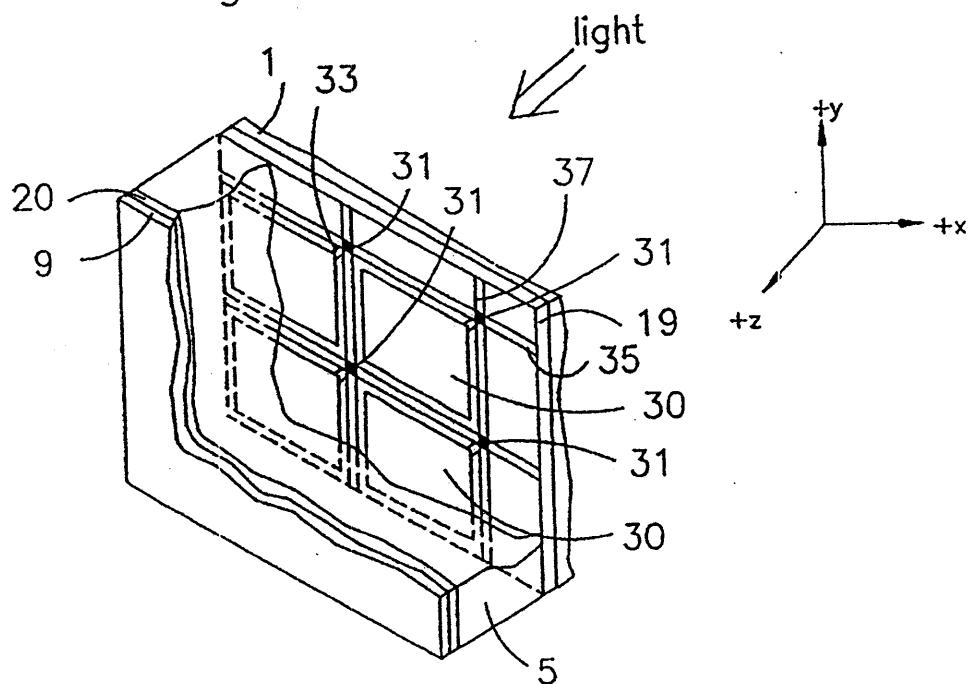
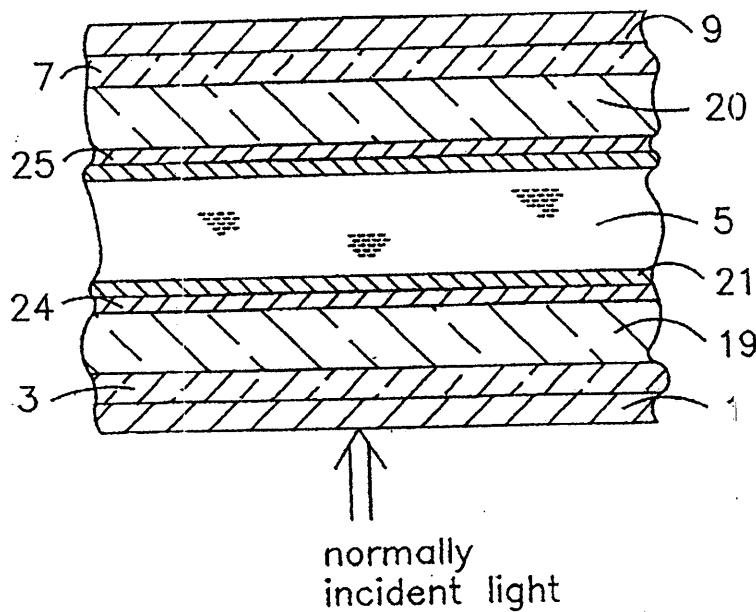


Fig. 41

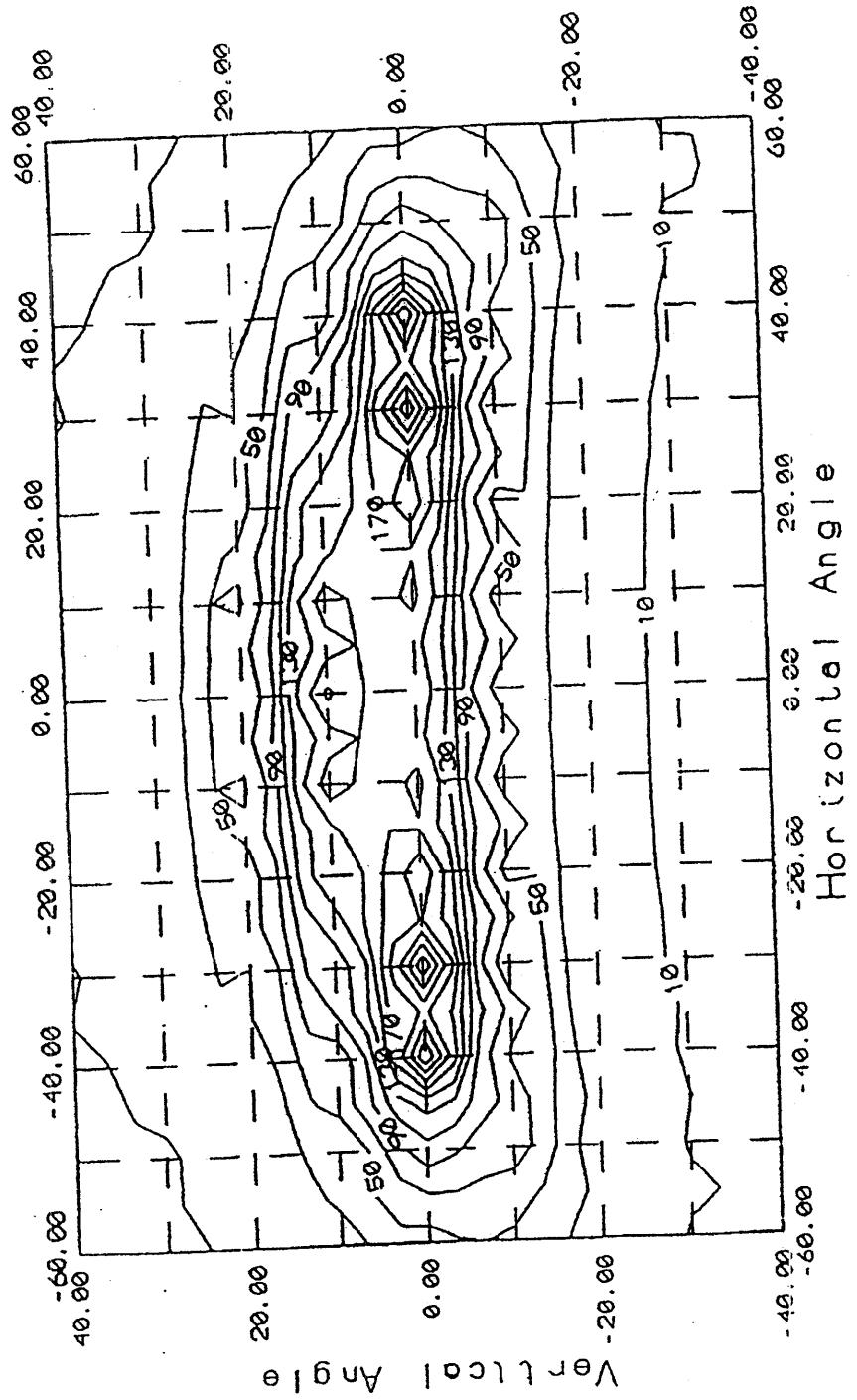


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$$\begin{aligned}V_{02} &= 6.0 \text{ V} \\Y &= 550 \text{ nm} \\R &= \Delta_{zx} = \Delta_{zy} = -160 \text{ nm}\end{aligned}$$

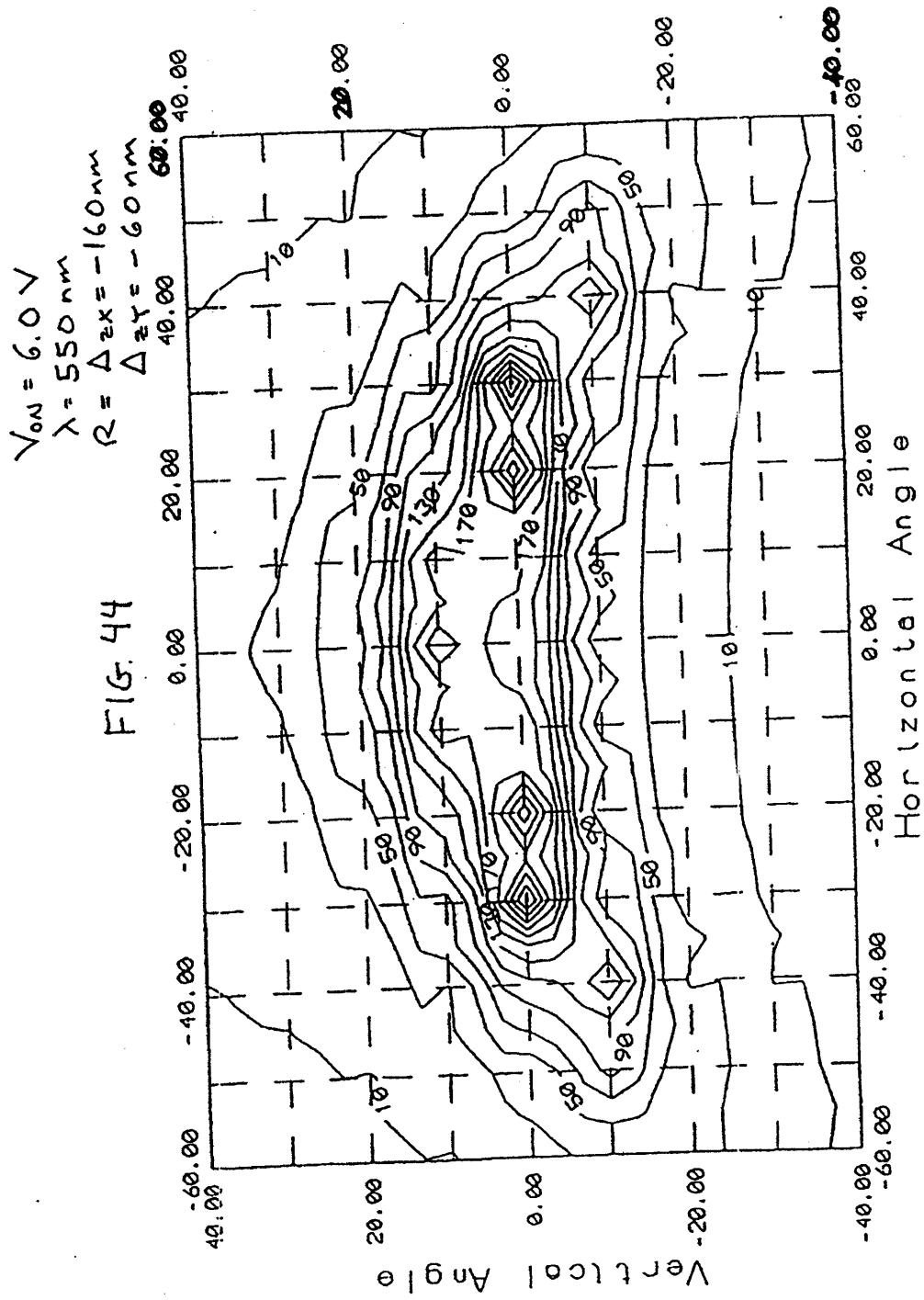
FIG. 43

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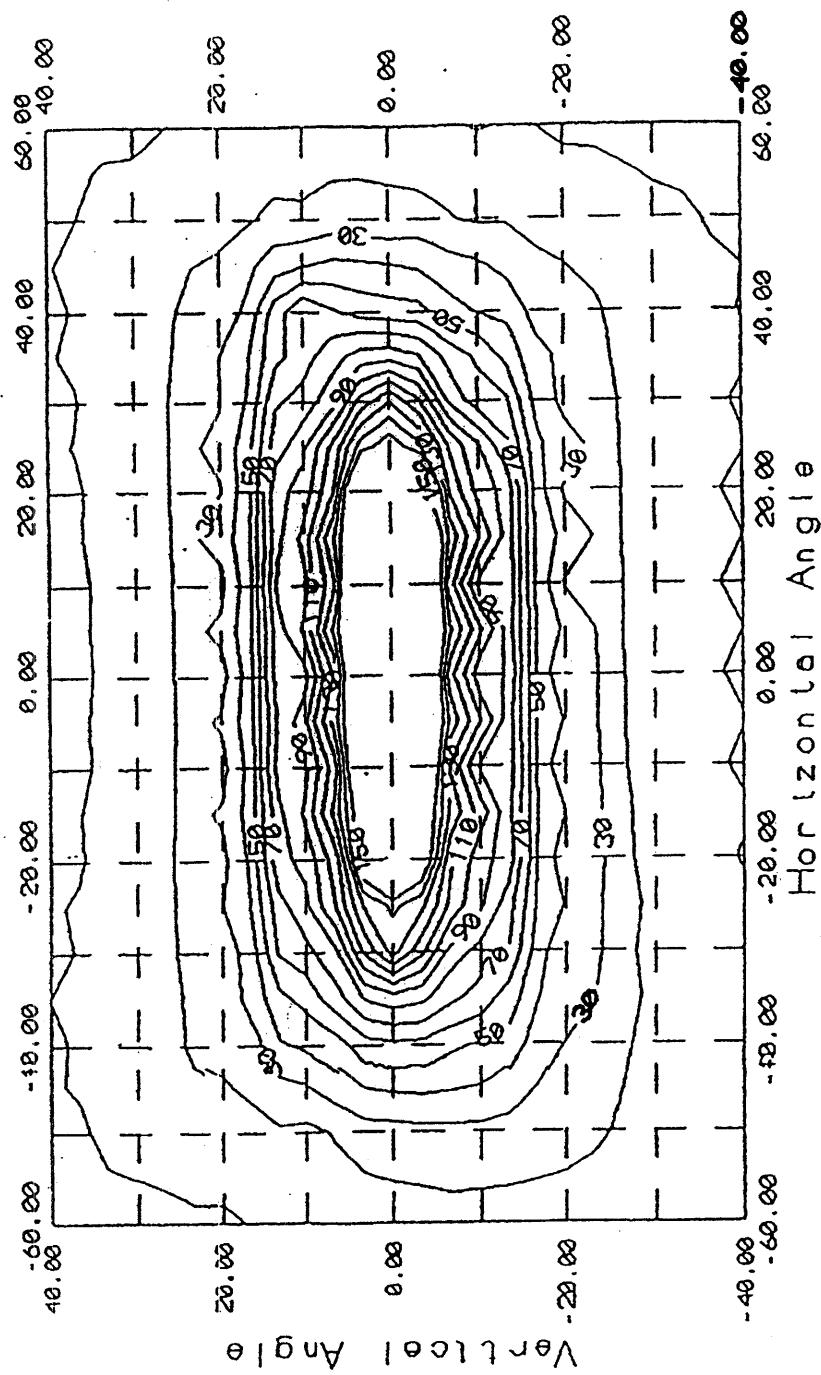


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$V_{on} = 6.0$
 $V = \text{WHITE}$
 $R = \text{BIAxIAL}$

FIG. 45

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1

**NORMALLY WHITE TWISTED NEMATIC
LCD WITH RETARDATION FILMS ON
OPPOSITE SIDES OF LIQUID CRYSTAL
MATERIAL FOR IMPROVED VIEWING
ZONE**

This invention relates to a liquid crystal display having at least two retardation films, one on each side of a liquid crystal layer. More particularly, this invention relates to a normally white liquid crystal display which includes at least one retardation film having a retardation value of 80-200 nm on each side of the liquid crystal layer.

BACKGROUND OF THE INVENTION

Liquid crystal materials are useful for electronic displays because light traveling through a layer of liquid crystal (LC) material is affected by the anisotropic or birefringent value (ΔN) of the material, which in turn can be controlled by the application of a voltage across the liquid crystal material. Liquid crystal displays are desirable because the transmission or reflection of light from an external source, including ambient light and backlighting schemes, can be controlled with much less power than was required for the illuminance materials used in other previous displays. Liquid crystal displays (LCDs) are now commonly used in such applications as digital watches, calculators, portable computers, avionic cockpit displays, and many other types of electronic devices which utilize the liquid crystal display advantages of long-life and operation with low voltage and power consumption.

The information in many liquid crystal displays is presented in the form of a matrix array of rows and columns of numerals or characters, which are generated by a number of segmented electrodes arranged in such a matrix pattern. The segments are connected by individual leads to driving electronics, which apply a voltage to the appropriate combination of segments to thereby display the desired data and information by controlling the light transmitted through the liquid crystal material. Graphic information in, for example, avionic cockpit applications or television displays may be achieved by a matrix of pixels which are connected by an X-Y sequential addressing scheme between two sets of perpendicular conductor lines (i.e. row and column lines). More advanced addressing schemes use arrays of thin film transistors, diodes, MIMs, etc. which act as switches to control the drive voltage at the individual pixels. These schemes are applied predominantly to twisted nematic liquid crystal displays, but are also finding use in high performance versions of super twisted liquid crystal displays.

Contrast is one of the most important attributes determining the quality of both normally white (NW) and normally (NB) liquid crystal displays. Contrast, or the contrast ratio, is the difference between OFF state transmission versus ON state transmission. In normally black liquid crystal displays, the primary factor limiting the contrast achievable in these LCDs is the amount of light which leaks through the display in the darkened or OFF state. In normally white (NW) LCDs, the primary factor limiting the contrast is the amount of light which leaks through the display in the darkened or ON state. These problems are compounded in a bright environment, such as sunlight, where there is a considerable amount of reflected and scattered ambient light. In color liquid crystal displays, light leakage causes severe color shifts for both saturated and gray scale colors. These limitations are particularly important for avionic applications.

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where the copilot's viewing of the pilot's displays is important.

In addition, the legibility of the image generated by both normally black (NB) and normally white (NW) liquid crystal display devices depends on the viewing angle, especially in the matrix address device with a large number of scanning electrodes. Absent a retardation film, the contrast ratio of a typical NB or NW liquid crystal display is usually at a maximum only within a narrow viewing (or observing) angle centered about normal incidence (0° horizontal viewing angle and 0° vertical viewing angle) and drops off as the angle of view is increased.

It would be a significant improvement in the art to provide a liquid crystal display capable of presenting a high quality, high contrast image over a wide field of view.

Normally black liquid crystal displays are quite sensitive to cell gap, or the thickness "d" of the liquid crystal material, as well as to the temperature of the liquid crystal material. Therefore, normally black liquid crystal displays must be manufactured in accordance with rather specific tolerance parameters related to the cell gap of the display making them both difficult and expensive to make. One way in which to compensate for the normally black displays high sensitivity to cell gap is to provide such a multi-colored display with a multi-gap design wherein the thickness "d" of the liquid crystal material for each colored subpixel is matched to the first transmission minimum of the color of that subpixel. See, for example, U.S. Pat. No. 4,632,514 which utilizes the multi-gap approach by varying the liquid crystal material thickness "d" for the red, green, and blue subpixels therein so as to match the thickness "d" of each subpixel to the three different transmission minimums representative of the colors red, green, and blue. This increases, of course, the difficulty and expense of manufacturing this type of LCD.

Although a normally black display is rather sensitive to temperature and cell gap "d", a significant advantage associated with this type of liquid crystal display is that it provides good contrast ratios at wide viewing angles. Thus, a viewer may satisfactorily observe the data of the display throughout a wide range of viewing angles. Contrast ratio curves of, for example, 10:1 in normally black displays often extend up to viewing angles of, for example, 0° vertical, ± 60 ° horizontal. The fact that normally black displays have such good contrast ratios at such large horizontal viewing angles enables them to be used in commercial applications where such viewing angles are required or preferred. Furthermore, NB displays generally experience more darkened state leakage than do NW displays at the normal viewing angle given current manufacturing technology.

Turning now to normally white liquid crystal displays, NW displays are fairly insensitive to the temperature and cell gap "d" of liquid crystal material. This allows for the manufacturing tolerances associated with the development of normally white displays to be lessened. Hence, normally white displays are easier and cheaper to manufacture than their normally black counterparts. However, while normally white LCDs are less sensitive to temperature and cell gap than normally black LCDs, their contrast ratios at large viewing angles are generally small relative to those of normally black displays. For example, 10:1 contrast ratio curves in normally white displays often only extend up to horizontal viewing angles of about 0° vertical, ± 35 ° horizontal. This is significantly less than the extent to which the same contrast ratio curves extend horizontally in normally black displays. Therefore, while normally white LCDs are easier and cheaper to manufacture than normally black

liquid crystal displays, they have a smaller range of satisfactory viewing angles than do normally black displays. It would satisfy a long felt need in the art if one could provide a NW display which had good contrast ratios at large viewing angles.

Several types of liquid crystal pixels or cells are in widespread use in flat panel displays. Active matrix addressing allows such displays to present a full color image with high resolution. When viewed directly at a normal or ON axis viewing angle (0° vertical, 0° horizontal viewing angle), a liquid crystal display of either the normally black or normally white type provides a generally high quality output, especially when the cell gap "d" is matched to the first transmission minimum, but the image degrades and contrast ratios decrease at increased viewing angles. This occurs because liquid crystal cells operate by virtue of the anisotropic or birefringent effect exhibited by their liquid crystal layer which includes a large number of anisotropic liquid crystal molecules. Such a material will be positively uniaxially birefringent (i.e., the extraordinary refractive index is larger than the ordinary refractive index). The phase retardation effect such a liquid crystal material has on light passing through it inherently varies or increases with the inclination angle of light, leading to lower contrast ratios and a lower quality image at larger viewing angles. By introducing an optical compensating element (or retarder) into the liquid crystal pixel or cell, however, it is possible to correct for the unwanted angular effects and thereby maintain higher contrast at both normal and larger viewing angles than otherwise possible.

The type and orientation of optical compensation or retardation required depends in part upon the type of display, normally black or normally white, which is used.

In a normally black (NB) twisted nematic display, the twisted nematic liquid crystal material is placed between polarizers whose transmission axes are parallel to one another. In the unenergized OFF state (no voltage above the threshold voltage V_{th} is applied across the liquid crystal material), normally incident light from the backlight is first polarized by the rear polarizer and in passing through the pixel or cell has its polarization direction rotated by the twist angle of the liquid crystal material dictated by the buffering zones. This effect is known as the twisting effect. The twist angle is set, for example, to be about 90° so that the light is blocked or absorbed by the front or output polarizer when the pixel is in the OFF state. When a voltage is applied via electrodes across the normally black pixel, the liquid crystal molecules are forced to more nearly align with the electric field, eliminating the twisted nematic optical effect of the LC material. In this orientation, the optical molecular axes of the liquid crystal layer molecules are perpendicular to the cell walls. The liquid crystal layer then appears isotropic to normally incident light, eliminating the twist effect such that the light polarization state is unchanged by propagation through the liquid crystal layer so that light can pass through the output polarizer. Patterns can be written in a normally black display by selectively applying a variable voltage to the portions of the display which are to appear illuminated.

Turning again to normally white (NW) LCD cells, in a normally white liquid crystal display configuration, a twisted nematic cell preferably having a twist angle of about 80°-100° (most preferably about 90°) is placed between polarizers which have substantially crossed or perpendicular transmission axes, such that the transmission axis of each polarizer is either parallel (P-buffed) or perpendicular (X-buffed) to the buffering direction or orientation of the liquid crystal molecules in the interface region of the liquid crystal

material adjacent each polarizer. In other words, normally white cells can be either P-buffed where both polarizer axes are substantially parallel to their respective adjacent buffering zones, or X-buffed where both polarizer axes are substantially perpendicular to their respective adjacent buffering zones.

This NW orientation of the polarizers reverses the sense of light and dark from that of the normally black displays discussed above. The OFF or unenergized (no applied voltage above V_{th} across the liquid crystal material) areas appear light in a normally white display, while those which are energized appear dark.

The problem of ostensibly dark areas appearing light or colored when viewed at large angles still occurs, however, thereby creating the aforesaid lowered contrast ratios at reasonably large viewing angles. The reason for the reduced contrast ratios at large viewing angles in normally white displays is different than the reason for the problem in normally black displays. In the normally white energized darkened areas, the liquid crystal molecules tend to align with the applied electric field. If this alignment were perfect, all of the liquid crystal molecules in the cell would have their long axes normal to the glass substrate or cell wall. In the energized state, the normal white display appears isotropic to normally incident light, which is blocked by the crossed polarizers, thus, resulting in a darkened pixel or subpixel.

The loss of contrast with increased viewing angles in normally white pixels or displays occurs primarily because the homeotropic liquid crystal layer does not appear isotropic to OFF axis or OFF normal light. Light directed at OFF normal angles through the liquid crystal material propagates in two modes due to the anisotropy or birefringence (ΔN) of the liquid crystal layer, with a phase delay between these modes which increases with the incident angle of light. This phase dependence on the incident angle introduces an ellipticity to the polarization state which is then incompletely extinguished by the front or exit polarizer in the normally white cell, giving rise to light leakage. Because of the normally white symmetry the birefringence has no azimuthal dependence.

Accordingly, what is needed in normally white displays is an optical compensating or retarding element which introduces a phase delay that restores the original polarization state of the light, allowing the light to be blocked by the output polarizer in the ON state. Optical compensating elements or retarders for normally white displays are known in the art and are disclosed, for example, in U.S. Pat. Nos. 5,184,236; 5,196,953; 5,138,474; and 5,071,997, the disclosures of which are hereby incorporated herein by reference. It is known that the polyimides and copolyimides disclosed by aforesaid U.S. Pat. No. 5,071,997 can be used as negative birefringent retarding elements in normally white liquid crystal displays and are said to be custom tailorable to the desired negative birefringent values without the use of stretching. The polyimide retardation films of U.S. Pat. No. 5,071,997 are uniaxial but with an optical axis oriented in the Z direction which is perpendicular to the plane defined by the film.

Quite often, the retardation films or plates used in conjunction with normally white displays have a negative birefringent value. However, in certain cases, retardation films having a positive birefringent value are used in combination with such normally white cells. An example of this is U.S. Pat. No. 5,184,236 which will be discussed more fully below.

FIG. 1 is a contrast ratio curve graph for a prior art normally white light valve pixel. The light valve for which

the contrast ratio curves are illustrated in FIG. 1 includes a rear polarizer having a transmission axis defining a first direction, a front or exit polarizer having a transmission axis defining a second direction wherein the first and second directions are substantially perpendicular to one another, a liquid crystal material having a cell gap "d" of 5.86 μ m, a rear buffering zone oriented in the second direction, and a front buffering zone oriented in the first direction. The temperature was 34.4° C. when the graph illustrated by FIG. 1 was plotted. This light valve pixel did not include a retarder. The above-listed parameters with respect to FIG. 1 are also applicable to FIGS. 2 and 3.

The contrast ratio graph of FIG. 1 was plotted utilizing a 6.8 V driving voltage V_{ON} , and a 0.2 volt V_{OFF} . As can be seen in FIG. 1, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis only to angles of about -40° horizontal and +38° horizontal. Likewise, the 30:1 contrast ratio curve extends along the 0° vertical viewing axis only to horizontal angles of about $\pm 30^\circ$. This graph is illustrative of the problems associated with normally white liquid crystal displays in that their contrast ratios at large horizontal and vertical viewing angles are fairly low.

FIG. 2 is a contrast ratio curve graph for the normally white light valve described above with respect to FIG. 1. However, the FIG. 2 graph was plotted utilizing a V_{ON} of 5.0 volts and a V_{OFF} of 0.2 volts. Again, the temperature was 34.4° C. As can be seen by comparing the graphs of FIG. 1 and FIG. 2, as the voltage applied to the liquid crystal material decreases, as in FIG. 2, the contrast ratio curves expand horizontally and contract vertically. The 10:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends a total of about 85° as opposed to only 78° in FIG. 1. Also, the 30:1 contrast ratio curve of FIG. 2 along the 0° vertical viewing axis extends horizontally about 67° as opposed to only about 58° in FIG. 1. With respect to vertical viewing angles, the contrast ratio curves of 10:1 and 30:1 in FIG. 2 do not extend along the 0° horizontal viewing axis to the negative vertical extent that they did in FIG. 1. Accordingly, while the normally white light valve of FIGS. 1-3 has less than desirable contrast ratios at large viewing angles, the contrast ratios expand horizontally and contract vertically as the voltage across the liquid crystal material decreases.

FIG. 3 is a driving voltage versus intensity plot for the light valve pixel described above with respect to FIGS. 1-2 illustrating the gray level characteristics of the pixel. The various curves represent horizontal viewing angles from -60° to +60° along the 0° vertical viewing axis.

Gray level performance of a liquid crystal display is very important. Conventional liquid crystal displays utilize anywhere from about eight to sixty-four different driving voltages. The different driving voltages are referred to as "gray level" voltages. The intensity of the light transmitted through the pixel or display depends upon the driving voltage. Accordingly, gray level voltages are used to generate different shades of different colors and to create different colors when these shades are mixed with one another. Preferably, the higher the driving voltage in a NW display, the lower the intensity of light transmitted therethrough. Likewise then, the lower the driving voltage, the higher the intensity of light emitted from the preferred forms of a normally white display. The opposite is true in a normally black display. Thus, by utilizing multiple gray level driving voltages, one can manipulate either an NW or NB liquid crystal display pixel to emit a desired intensity of light. A gray level V_{ON} is any voltage greater than V_{th} up to about 5.0-6.5 V.

Gray level intensity performance for LCDs is dependent upon the displays' driving voltage. It is desirable in gray

level performance of NW displays to have an intensity versus driving voltage curve wherein the intensity of the light emitted from the pixel continually and monotonically decreases as the driving voltage increases. In other words, it is desirable to have gray level performance in a pixel such that the intensity at 6.0 volts is less than that at 5.0 volts, which is in turn less than that at 4.0 volts, which is less than that at 3.0 volts, which is in turn less than that at 2.0 volts, etc. Such good gray level curves across wide ranges of viewing angles allow the intensity of radiation emitted from the pixel to be easily controlled.

Turning again now to FIG. 3, the intensity versus driving voltage curves illustrated therein with respect to the prior art light valve pixel of FIGS. 1-2 having no retardation film are undesirable because of the inversion hump present in the area of the curves having voltages greater than about 3.2 volts. The term "inversion hump" means that the intensity aspect of the curve monotonically decreases as the driving voltage increases in the range of about 1.6-3.0 volts, but at a driving voltage of about 3.2 volts, the intensities at a plurality of viewing angles begin to rise as the voltage increases from about 3.2 volts to 6.8 volts. This rise in intensity as the voltage increases is known as an "inversion hump." The inversion hump of FIG. 3 includes only a rise portion. However, such inversion humps often include both a rise and fall portion. The presence of this inversion hump with respect to a plurality of horizontal viewing angles as shown in FIG. 3 means that as gray level voltages between, for example, 1.6 and 3.0 volts increase, the intensity of radiation emitted from the pixel decreases accordingly. However, as gray level voltages above 3.0 volts increase from 3.2 volts all the way up to 6.8 volts, the intensity of radiation emitted from the pixel increases. This is undesirable. A perfect driving voltage versus intensity curve would have a decreased intensity for each increase in gray level driving voltage. In contrast to this, the inversion hump represents an increase in intensity of radiation emitted from the light valve pixel for each increase in gray level driving voltage above about 3.2 volts for certain viewing angles. Accordingly, it would satisfy a long felt need in the art if a liquid crystal display and pixels therein could be provided with no or little inversion. In other words, the smaller the rise in intensity for an increase in driving voltage at all gray levels, the better.

FIG. 4 is a schematic illustration showing an optical arrangement of a normally white liquid crystal display device disclosed in U.S. Pat. No. 5,184,236. As illustrated, the LCD includes a rear polarizer 111, a rear retardation plate or film 113, a liquid crystal cell 119 including a liquid crystal material sandwiched between a rear orientation or buffering zone oriented in direction A_0 and a front orientation or buffering zone oriented in direction A_1 , a front retardation film 114, and finally a front polarizer 112.

The rear polarizer 111 is provided at the light incident side of the liquid crystal layer 119, a front or exit polarizer 112 is provided at the light exit side of the liquid crystal layer 119, a rear retardation film 113 is provided between the liquid crystal layer and the polarizer 111, and a front retardation film 114 is provided between the liquid crystal layer and the front polarizer 112. This prior art NW display is "P-buffed" because the rear polarizer transmission axis P_1 is parallel to the rear orientation direction A_0 , and the front polarizer transmission axis P_2 is parallel to the front orientation direction A_1 .

The product of parameters " $\Delta N \cdot d$ " of the liquid crystal layer 119 is set in the range of 450-550 nm. The liquid crystal material of U.S. Pat. No. 5,184,236 is left handed as

5,570,214

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defined in the art. The aligning direction of the rear orientation film on the light incident side of the liquid crystal layer 109 is a rubbing direction A_0 inclined at approximately 45° with respect to the side of the liquid crystal cell. The aligning direction of the orientation or buffering film on the front side of the liquid crystal layer is oriented in direction A_1 which is rotated about 90° in a counterclockwise direction from the orientation direction A_0 of the orientation film on the rear side of the liquid crystal material. Therefore, the liquid crystal layer 119 sandwiched between the opposing orientation films is twisted substantially 90°. The pretilting angle of the liquid crystal molecules is approximately 1°.

The rear linear polarizer 111 has a transmission axis P_1 which is parallel to the orientation direction A_0 , while the front polarizer 112 has a transmission axis direction P_2 which is parallel to the front orientation direction A_1 . The transmission axes of the front and rear polarizers 112 and 111 are perpendicular to one another thereby defining a normally white liquid crystal display. The rear retardation plate or film 113 is so arranged that its optical axis R_1 is either parallel to or crosses at 90° to the rear rubbing direction A_0 . The front retardation film 114 is so arranged that its optical axis R_2 is either parallel to or crosses at 90° to the rubbing direction A_1 . These retardation films 113 and 114 are formed to have equal retardation values ($d\Delta N$) where "d" is the thickness of the retardation film and " ΔN " is the anisotropic or birefringent value of the retardation film. The retardation values of the retardation films 113 and 114 are set in the range of 300-400 nm. The front and rear retardation films are formed of the same material such as, for example, a polycarbonate or polyvinyl alcohol, and the outer surfaces thereof are preferably covered with a protective film made of triacetyl cellulose or the like.

The orientation or buffering directions of prior art FIG. 4 are "six o'clock buffered." The term "six o'clock buffered" means that the rear and front orientation directions A_0 and A_1 are oriented in directions so as to provide a viewing zone having an extended region in the six o'clock area of the graphs shown in FIGS. 5A-5D. In other words, because the orientation direction A_0 goes from the upper left to the lower right as shown in FIG. 4, and orientation direction A_1 goes from lower left to upper right, the resulting viewing zone has better contrast as shown in FIGS. 5A-5D in the negative vertical region below the 0° vertical viewing axis. This is what is meant by the phrase "six o'clock buffered."

Alternatively, if the orientation direction A_0 went from the lower right to the upper left, and the orientation direction A_1 was directed from the upper right to the lower left, then the display of FIG. 4 would have been "twelve o'clock buffered" and would have provided a viewing zone having better contrast ratios in the positive vertical viewing angles instead of the negative vertical viewing angles. The six o'clock buffered LCDs of FIGS. 4 and 5A-5D illustrate viewing zones with better contrast ratios in the negative vertical area below the 0° vertical viewing axis as opposed to the positive vertical viewing area above the 0° vertical viewing axis.

In the prior art liquid crystal display of FIG. 4, the contrast ratios are measured in FIGS. 5A-5D for the four possible cases of retardation film orientation, when the value of $d\Delta N$ of a liquid crystal layer 119 is set to 510 nm and the retardation value of both retardation films 113 and 114 is set to 350 nm (the value measured by the light having a wavelength of 589 nm). The four cases are as follows.

FIG. 5A shows contrast ratio curves for the case where the optical axes of the rear and front retardation films 113 and 114 are disposed together in parallel to the rear rubbing

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direction A_0 . The solid or outer contrast ratio curve in FIGS. 5A-5D represents a contrast ratio of 10:1. The inner or equally broken contrast curve in FIGS. 5A-5D represents a contrast ratio of 100:1. The intermediate contrast ratio curve in FIGS. 5A-5D represents a contrast ratio of 50:1. Furthermore, in the graphs of FIGS. 5A-5D, each circle represents a 10° shift in viewing angle. In other words, the center of the graph represents a 0° vertical and 0° horizontal viewing angle, the first circle represents 10°, the second circle 20°, etc. As can be seen in FIG. 5A, the 10:1 contrast ratio curve extends horizontally along the vertical 0° viewing axis to about -37° and +40°, and extends upward along the 0° horizontal viewing axis to about 15° vertical.

FIG. 5B shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film 113 is disposed in parallel to the orientation direction A_0 , and the optical axis R_2 of the front retardation film 114 is disposed perpendicular to the rubbing direction A_0 . The direction R_1 is parallel to the rear polarizer axis P_1 , and R_2 is parallel to the front polarizer axis P_2 . As can be seen in FIG. 5B, the 10:1 contrast ratio curve extends along the 0° horizontal viewing axis only to about 15° vertical. Also, the 50:1 contrast ratio curve extends along the 0° horizontal viewing axis only to about 5° vertical.

FIG. 5C shows contrast ratio curves for the case where the optical axes of the rear and front retardation films 113 and 114 are arranged in parallel with one another and cross at 90° to the rear buffering direction A_0 . In FIG. 5C, the 10:1 contrast ratio curve extends upward along the 0° horizontal viewing axis only to about 15° vertical. Also, the 10:1 contrast ratio curve extends along the 0° vertical viewing axis a total of about 75°-80°.

FIG. 5D shows contrast ratio curves for the case where the optical axis R_1 of the rear retardation film 113 is arranged to cross at 90° to the rubbing direction A_0 , and the optical axis R_2 of the front retardation film 114 is arranged in parallel to rear orientation direction A_1 . In FIG. 5D, the 10:1 contrast ratio curve extends horizontally along the 0° vertical viewing axis a total of about 60°-65°. Also, the 10:1 contrast ratio curve in FIG. 5D extends upward along the 0° horizontal viewing axis only to about +15° vertical.

It was known prior to our invention to rotate retardation films to adjust the viewing zones of LCDs. For example, U.S. Pat. No. 5,184,236 teaches rotating the optical axes of retardation films $\pm 15^\circ$ or less when two such films are disposed on a single side of the liquid crystal material. The axes of the retardation films are rotated either in the clockwise or counterclockwise direction for the purpose of adjusting the viewing zone. However, when the retardation films of this patent are rotated, the symmetry of the viewing zone is substantially distorted thereby creating viewing zones which are not substantially symmetrical about the 0° horizontal viewing axis. Furthermore, this patent does not teach rotating one or both optical axes of rear and front retardation films $\pm 15^\circ$ or less for the purpose of adjusting the location of the display's viewing zone when the display includes rear and front retardation films with a liquid crystal layer therebetween.

FIG. 6 illustrates the angular relationships between the horizontal and vertical viewing axes and angles described herein relative to a liquid crystal display and conventional LCD angles ϕ and Θ . The +X, +Y, and +Z axes shown in FIG. 6 are also defined in other figures herein. Furthermore, the "horizontal viewing angles" (or X_{ANG}) and "vertical viewing angles" (or Y_{ANG}) illustrated and described herein may be transformed to conventional LCD angles ϕ and Θ by the following equations: